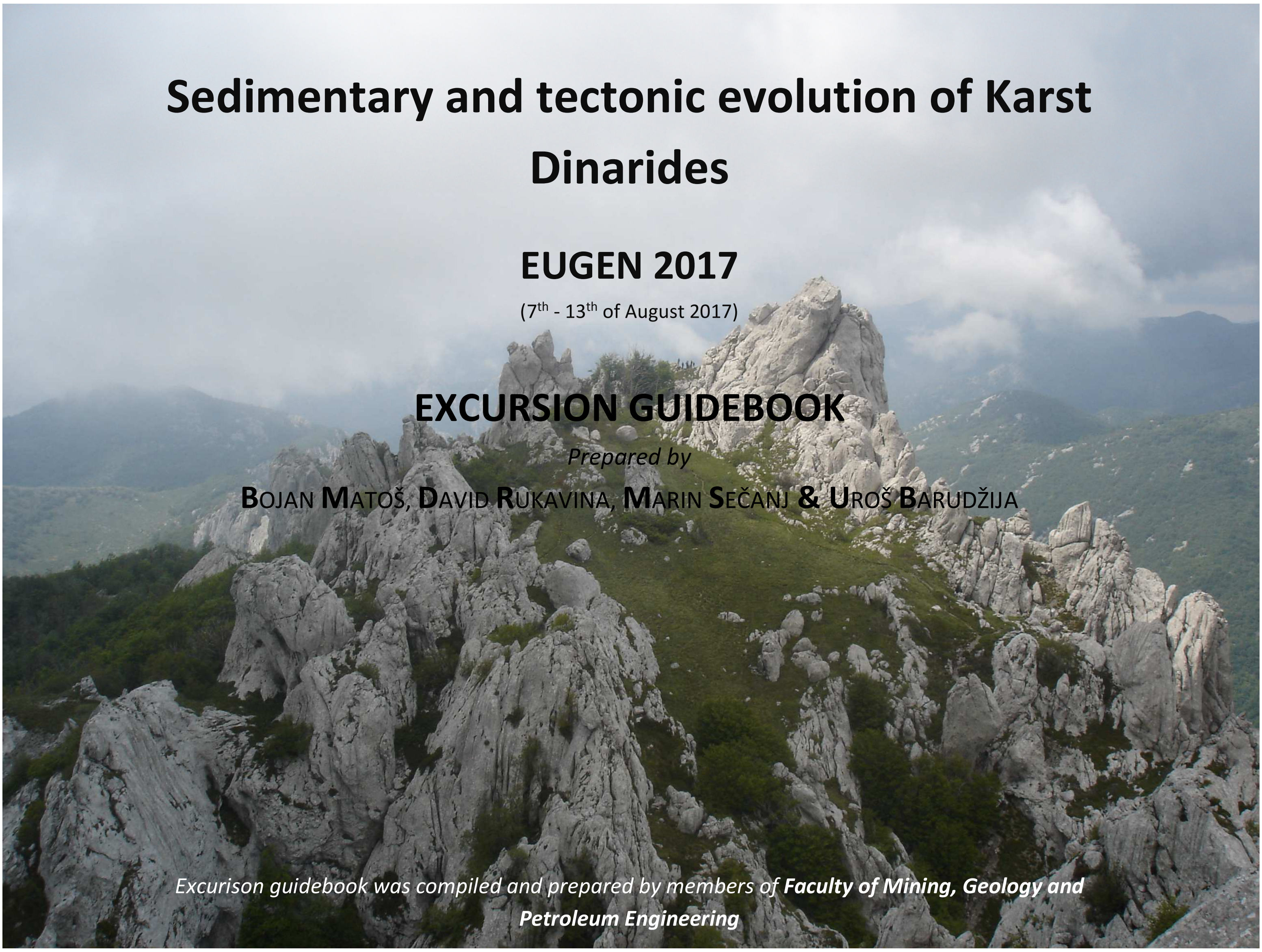

Sedimentary and tectonic evolution of Karst Dinarides

EUGEN 2017

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EXCURSION GUIDEBOOK

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Content

List of figures

karst spring and (c) contact along fault between the carbonates in which we can see folds and underlying carbonates in the Curak stream of complitelly different orientation.

Fig. 17. Photo of the waterfall gushing next to the Green Whirlpool spring with clearly visible fold next to it.

Fig. 18. Schematic overview of the formation of the stream Curak and Jasle canyon where: (a) represents the faze after nappe tectonics took place, (b) initial faze of opening after extensional tectonics and (c) final phase after weathering.

Fig. 19. Fault plane of a normal fault in the stream Jasle canyon.

Fig. 20. Profile and scheme of the Muževa Hiža cave (original schematics by Vlado Božić and Ivica Posarić, SO HPD Željezničar; edited by Ivana Gudac)

Fig. 21. Photos of the entrance of the Muževa Hiža cave (upper photo) and of the two boats at the end of the cave (bottom photo).

Fig. 22. Geological profile of Mt. Velebit (after Sokač et al. 1974). See **Fig. 13** for profile location. Legend: **C_3-** Carboniferous shale, conglomerate and andstone; **P_2-**Middle Permian sandstone; **$P_{2,3}$-**Middle-Upper Permian dolomite; **$^{1,2,3}T_1$-**Middle-Uppermost Lower Triassic dolomites with terrigenous clastics; **T_2^1-** Anisian limestone and dolomite with clastic intercalations; **$T_3^{2,3}$-** Upper Triassic dolomite; **J_1^{1+2}-** Lowermost Jurassic limestone, subordinate dolomites; **J_1^3-** Middle Lower Jurassic limestones; **J_1^4-** Uppermost Lower Jurassic limestones and subordinate dolomites; **J_2-** Middle Jurassic limestones and dolomitized limestones; **$J_3^{1,2}$-** Upper Jurassic limestones; **$K_2^{1,2}$-** Upper Cretaceous (Cenomanian-Turonian) limestones and dolomites; **K_2^3-** Upper Cretaceous (Santonian) limestones; **$E_{1,2}$-** Eocene foraminiferal limestone dolomite; **E,Ol-** Eocene, Oligocene limestones, conglomerates and breccias (Velebit breccia).

Fig. 23. Recent structural arrangement of the External Dinarides in the central portions of Dinarides. (after Korbar, 2009).

Fig. 24. Geological map of central Mt. Velebit area (after Sokač et al., 1974) with numbered geological stops along the road Rizvanuša - Karlobag. Geological profile A-B is illustrated in **Fig. 22.**

Fig. 25. Carboniferous shales in Rizvanuša village.

Fig. 26. Carboniferous shales and conglomerates in Rizvanuša village.

Fig. 27. Middle Permian Brušane sandstones along Gospić – Karlobag road.

Fig. 28. Košna spring – "Košna" conglomerates from Middle Permian.

Fig. 29. Karvarija location with Limestones from Middle to Upper Permian carbonate succession.

Fig. 30. Paripov jarak location on the Gospić – Karlobag road with Upper Permian carbonates.

Fig. 31. Gospić – Karlobag road in the vicinty of eastern entrance of Baške Oštarije where Permian – Triassic boundary is exposed.

Fig. 32. Outcrop of *Diplopora limestone* in the vicinity of settlement Prpići.

Fig. 33. Detail of the *Diplopora limestone* with makroscopically visible remnants of *Diplopora annulata* (road Sv. Rok-Mali Alan-Obrovac- *c. 45 km SW)*.

Fig.34. Microscopic section of microfacies of *Diplopora annulata* SCHAFHÄUTL and Kantia dolomitica PIA. Sv. Rok–Mali Alan Road, Ladinian. Each ring (annulum) bears two whorls of trichophorous branches (after Sokač, 2007)

Fig. 35. Outcrop of Upper Triassic red clastic series above *Diplopora limestone* in the vicinity of settlement Prpići.

Fig. 36. A) Outcrop of red clastics and conglomerates c. 6 km to the NE (locality of Jadovno). B) Outcrop conglomerate detail.

Fig. 37. Shematic geological column of Vrance locality (c. 60 km to the SE, near Gračac; see Tišljar et al., 2007 for details).

Fig. 38. Outcrop of Upper Norian? carbonates just above Upper Triassic red clastic series and *Diplopora limestone* in the vicinity of settlement Prpići.

Fig. 39. A.Landscape in Hauptdolomite formation in the vicinity of settlement of Prpići-Baške Oštarije. B. Fragments of late-diagenetic dolomites covering landscape formed within Hauptolomite formation.

Fig. 40. Outcrop detail of early-diagenetic dolomites within Hauptdolomite formation.

Fig. 41. Outcrop of Lower Jurassic limestone and dolomite succession at theBadanj peak (1164 m).

Fig. 42. Outcrop of Lower Jurassic limestone and dolomite succession at the Kubus pass(1044 m). Strata are characterized by steeply inclined bedding planins, and strata with c. 30-100 cm thickness.

Fig. 43. Microscopic section of microfacies of *Palaeodasycladus mediterraneus* var. *heraki, Palaeodasycladus mediterraneus* var. mediterraneus, *Palaeodasycladus mediterraneus* var. *gracilis..* Bundles of secondary branches are clearly visible. Sample localities and ages--VT: Mali Alan Pass, central Mt. Velebit, Lower L iassic; JD: Jadičevac, central Mt. Velebit, Lower Liassic; TG: Mt. Trnovski Gozd, western Slovenia, Middle Liassic (after Sokač, 2001).

Fig. 44. Middle Lower Jurassic Lithiotides limestone unit steeply inclined towards SW *(c. 300 m W in relation to Kubus pass).*

Fig. 45. Middle Lower Jurassic Lithiotides limestone detail with Lithiotis shells.

Fig. 46. Microscopic section of 1–4 Orbitopsella primaeva (HENSON), Late Sinemurian–Early Pliensbachian; 1 – megalosphaeric and microsphaerc forms, 2–4 – microsphaeric forms; 1, 3–4: North Velebit Mt., 2: Central Velebit Mt., Croatia. 5–6 Orbitopsella praecursor (GÜMBEL), Pliensbachian; megalosphaeric forms, 5: Central Velebit Mt., 6: Plitvice, Croatia. 5–8 Lituosepta recoarensis CATI, Late Sinemurian–Early Pliensbachian; 5–6: Central Velebit Mt., 7–8: Gornje Jelenje, Croatia. 9–10 Orbitopsella primaeva (HENSON), Late Sinemurian–Early Pliensbachian; megalosphaeric forms, 9–10:South Velebit Mt., 11: North Velebit Mt. Scale bars – 0.2 mm (after Velić, 2007).

Fig. 47. Fleckenkalk, "Spotty" limestone unit at Stop 11 (c. 2 km from Kubus pass, along the road towards the Karlobag).

Fig. 48. Fleckenkalk, "Spotty" limestone unit in detail with fossil bioturbations.

Fig. 49. Massive carbonate polimiknic breccia in the footwall of Kiza peak (1274m).

Fig. 50. An overview of Tulove grede, part of Mt. Velebit peaks composed of c. 600 m of Velebit breccia unit (*in the SW part of Mt. Velebit, in vicinity of Sv. Rok tunnel*).

Fig. 51. Velebit/Jelar breccia unit. Examples with greyish and redish matrix. This massive breccia is consisted of clasts of Mesozoic and Paleogene sedimentary rocks.

Fig. 52. Map showing the schematic distribution of large-scale sequences in Istria and the location of the Western Istrian anticline (partly modified after VELIĆ et al., 1995a), with locations of the excursion stops. Deposits of all large-scale sequences of Istrian carbonates and flysch are for the most part irregularly covered by relatively thin Quaternary deposits (5th large-scale sequence).

Fig. 53. Carbonate breccias and flysch deposits in the vicinity of settlement Čiritež.

Fig. 54. Lower Aptian oncoidal limestones in Kanfanar quarry.

Fig. 55. Berriasian early- and late-diagenetic dolomites in Fantazija quarry.

Fig. 56. Zlatni Rt cape (**S of Rovinj**), with 1st large-scale sequence (Bathonian–Oxfordian/lowermost Kimmeridgian) and the beginning of the second large-scale sequence (Upper Tithonian–Lower/Upper Aptian) of Istrian deposits.

1. Introduction

The Dinarides, a NW-striking mountain chain along the NE Adriatic coast characterize of c. 700 km long orogen that connect Southern Calcareous Alps to the north and Albanides and Hellenides-Taurides to the south. (Pamić et al., 1998; Vlahović et al., 2012). These mountain chain, a product of alpine orogeny, is consisted from thick and strongly tectonized sedimentary succession with stratigraphic range from Carboniferous to Quaternary (**Fig. 1**).

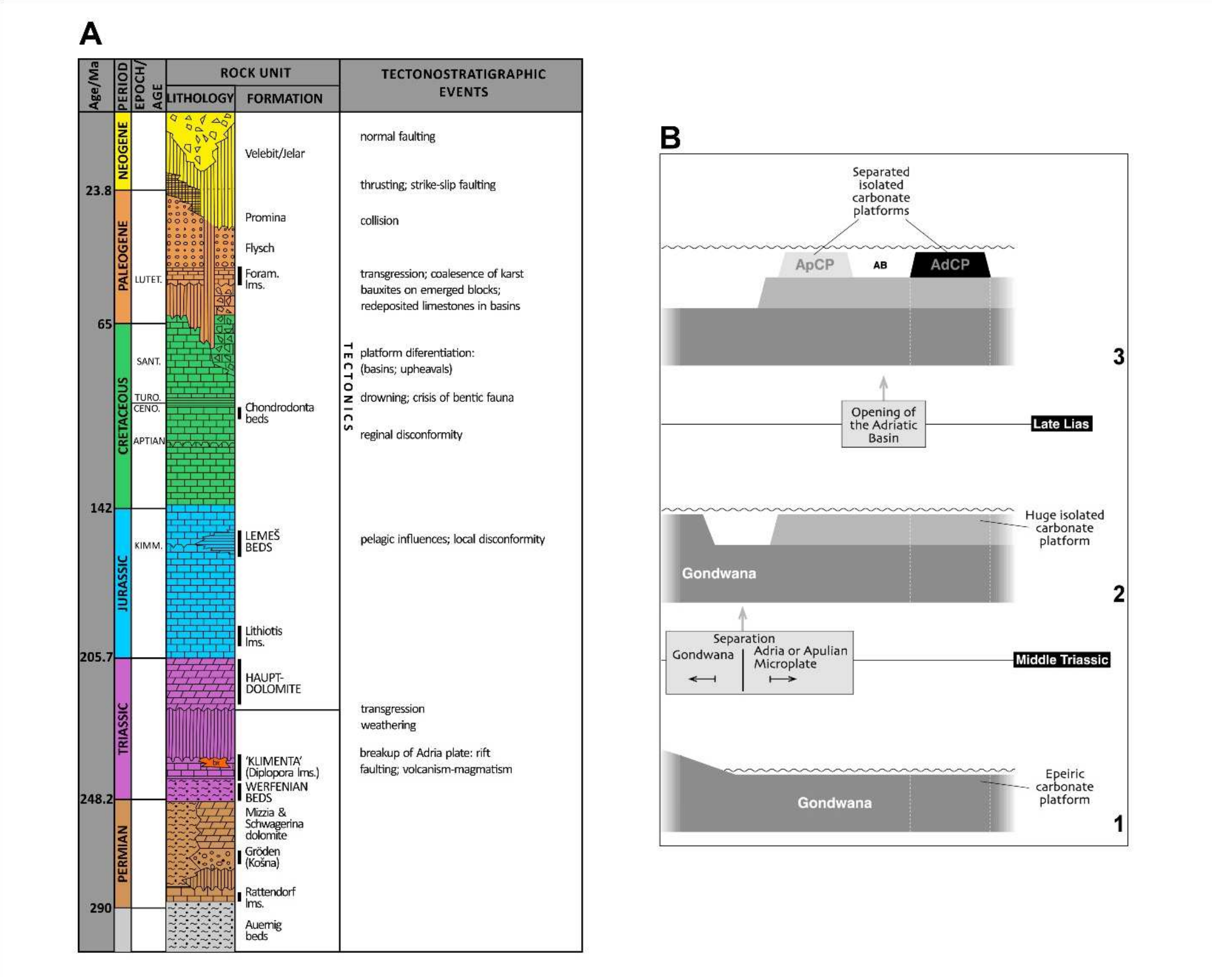


Fig. 1. A. Shematic geological column with sedimentary sequences of the Outer or Karst Dinarides (after Jelaska, 2003). **B**. Illustration that depict main events in tectonic evolution of Adriatic Carbonate Platform. 1. Study area until middle Triassic rifting that is characterized by epeiric platform along the Gondwana margin. 2. Adria Microplate separation from Gondwana and formation of Adriatic Basin and Molise-Lagonero Basin Lower Jurassic. 3. Formation of Adriatic Carbonate Paltform with carbonate deposition until Late Cretaceous. Formation of Apulian Carbonate Platform and Apenninic Carbonate Platform (after Velić et al., 2003).

The evolution of the Dinarides was controled by a series of tectonic events within Alpine orogenic cycle (between Late Permian to Oligocene), however the main imprint was tectonic uplift and formation of imbricated nappe system during Late Eocene to Oligocene time that resulted in fold-and-thrust belt of Dinarides (Pamić et al., 1998). As a result, Dinaridic mountain chain is composed from several tectonic units that are derived on both Adriatic Microplate in SW (present day coordinate system) and its contact zone with European plate in NE (Tari, 2002, with references).

According to Vlahović et al. (2005, with references) and Schmid et al (2008, with references), orogenic system of Dinarides could be subdivided into two main tectonostratigraphic units (**Figs. 2** and **3**):

a) ***Outer or Karst Dinarides***, i.e., ***External Dinaridic Platfom*** that is composed of tectonic units of Dalmatian Zone, Budva-Cukali Zone and High Karst Unit, and

b) ***Internal Dinarides***, i.e., ***Internal Dinaridic Platfom*** that is composed of tectonic units of Pre-Karst and Bosnian Flysch Unit, thrust sheets of East Bosnian-Drumitor, Drina-Ivanjica and Jadar-Kopaonik, Ophiolites obducted on Adria Margin, and Sava Zone that resembles Cenozoic suture between Dinarides and Tisza-Dacia Mega-Unit.

Outer or Karst Dinarides (**Figs. 2 an 3**) are mainly composed of an impressive carbonate ssucession deposited on Adriatic Carbonate Platform (AdCP) that commenced in "*sensu lato*" already in Carboniferous, Late Permian and Triassic, however, in "*sensu stricto*" carbonate succession deposited on AdCP were formed in main portion during Jurassic and Createaceous (**Fig. 1**; Velić et al. 2003; Vlahović et al., 2005; Vlahović et al., 2012 with references). Beside carbonate succession that was build over c. 250 Ma (with total tickness of c. 8 km) in relatively stable shallow-marine enviroments, Outer Dinarides comprise subordinately interspersed deep-water sediments deposited in narrow deep-water troughs (e.g Budva Zone; see Schmid et al. 2008 for details).

The more inland area, between Outer Dinarides and Pannonian Basin, the area of Internal Dinarides tectonostratigraphic unit (**Figs. 2** and **3**) is mainly composed of deep-water succession deposited on the passive margin of Adria Microplate (Schmid et al., 2008 with references). Accordingly, it is composed of passive continetal margine carbonate-clastic series, ultarmafics and deep-water sediments of ophiolitic complexes, ophiolitic mélange units, flysch-like, and bimodal magmatic and metamorphic rocks that compose formations within Sava Suture Zone (Pamić et al., 1998; Schmid et al., 2008 with references).

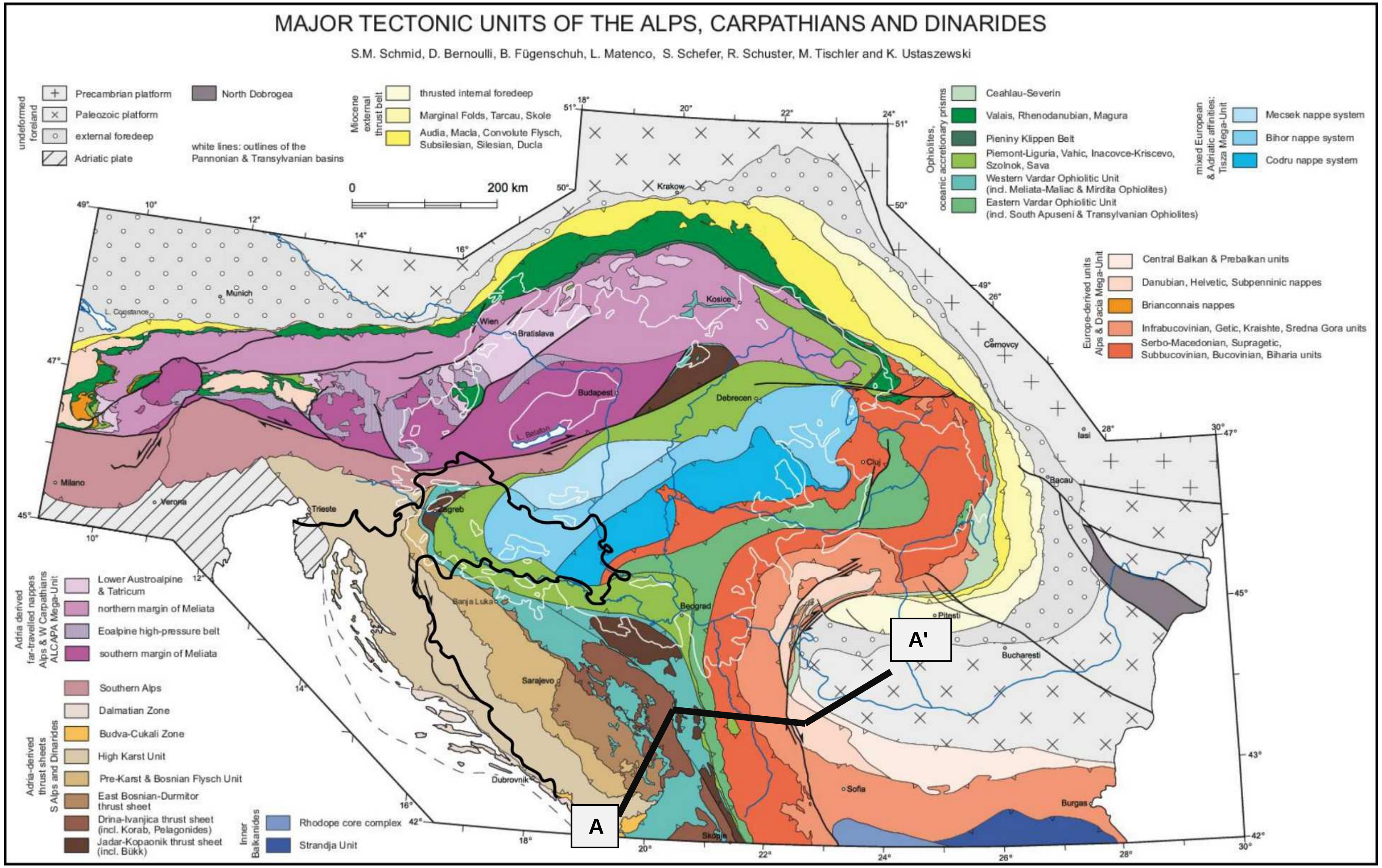


Fig. 2. Geotectonic units of Alps, Carpathians, Dinarides and Pannonian Basin System. See **Fig. 3** for profile (after Schmid et al., 2008)

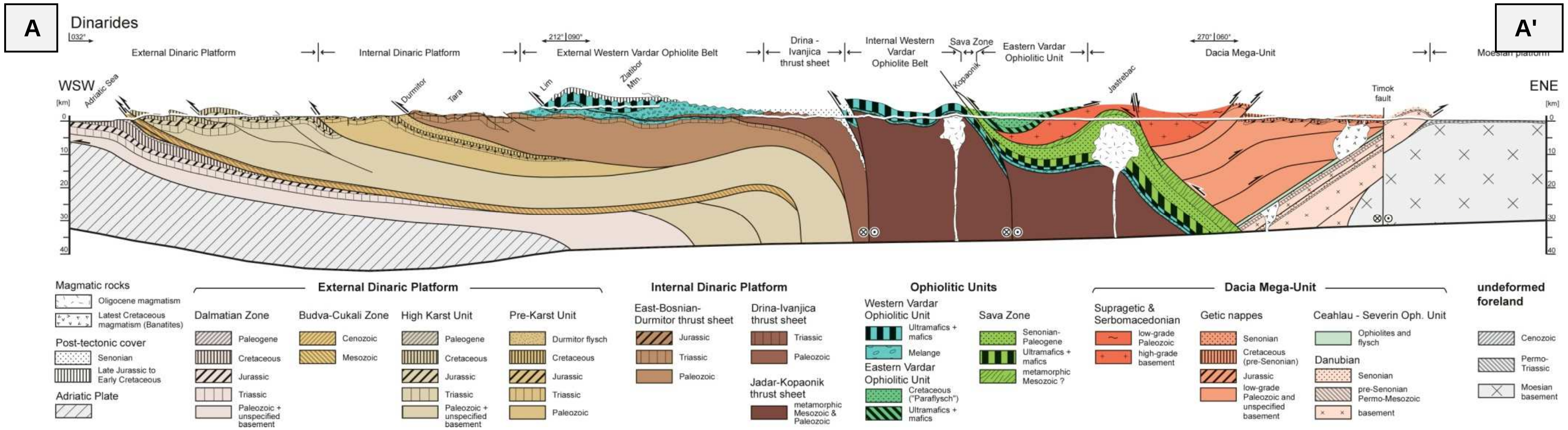


Fig.3. Schematic cross sections across the Dinarides, Sava Zone and Dacia Mega-Unit (after Schmid et al., 2008).

2. Adriatic Carbonate Platform (AdCP)

Tectonic and sedimentary evolution of te Karst Dinarides is genetically linked with Adriatic Carbonate Platform (**AdCP**; **Fig. 4**), formed on the Adria Microplate as a vast, relatively stable shallow-marine area (Vlahović et al., 2012). This area, c. 80-200 km wide and nearly 700 km long, as one of the largest Mesozoic carbonate platforms (**Fig. 4**) in the Perimediterranean region was characterized by continous deposition of carbonate succession that in places reach c. 8000 m and ranges in age from the Middle Permian (or even Late Carboniferous) to Eocene (Vlahović et al., 2005).

Sedimentary sucession of the AdCP begins with Carboniferous to Middle Triassic siliciclastic–carbonate deposits accumulated along the Gondwanian margin, on a spacious epeiric carbonate platform (**Fig. 1**). Onset of AdCP formation was characterized by Middle Triassic volcanism i.e., continental rifting, that due to extension and formation of deep normal faults enabled break up od Adria Microplate (Pamić et al., 1998) and formation of isolated carbonate ***Southern Tethyan Megaplatform*** with the area of the future AdCP (Vlahović et al., 2005).

This also point out that in Middle/Late Triassic to Lower Jurassic AdCP was considerably extended, characterized by mostly continious shallow-marine carbonate deposition including Upper Triassic Hauptdolomit and Lower Jurassic limestones (e.g. Lithiotid limestone). Beside AdCP, in middle to late Early Jurassic ***Southern Tethyan Megaplatform*** (**Fig. 4**) was dismembered into several other carbonate platforms (e.g., Apenninic and Apulian; see **Fig. 4**) isolated by deeper marine areas (e.g., Adriatic Basin, Ionian and Belluno basins, Lagonero Basin, and Slovenian and Bosnian troughs; Vlahović et al., 2005 with references therein). Common characteristic of these Mesozoic carbonate platforms was dominant shallow-marine carbonate deposition due to gradual subsidence, with periods of emergence due to either synsedimentary tectonics or eustatic changes. Environments ranged from peritidal through shallow subtidal–lagoons, restricted inner platform shallows, high-energy tidal bars, beach and shoreface to reefal–perireefal areas, with carbonate slope deposits in the areas of drowned platform and intraplatform troughs (Tišljar et al., 2002; Vlahović et al., 2005 with references).

Besides tectonic activity that formed shallow intraplatform trough (e.g. Gorski kotar and Knin area), dominant shallow-marine depositional rates were influenced by environment energy and global events, i.e., anoxic events (OAE- see Valhović et al., 2005 and references therein), which resulted in specific lithotype deposition and depositional cycles from high energy oolitic limestones to heavily bioturbated limestones. Accordingly, during the 125 Myr of the AdCP's existence, trough Late Triassic, Jurasic and Cretaceous the thickness of deposited limestone and dolostone reached between 3500 and 5000 m.

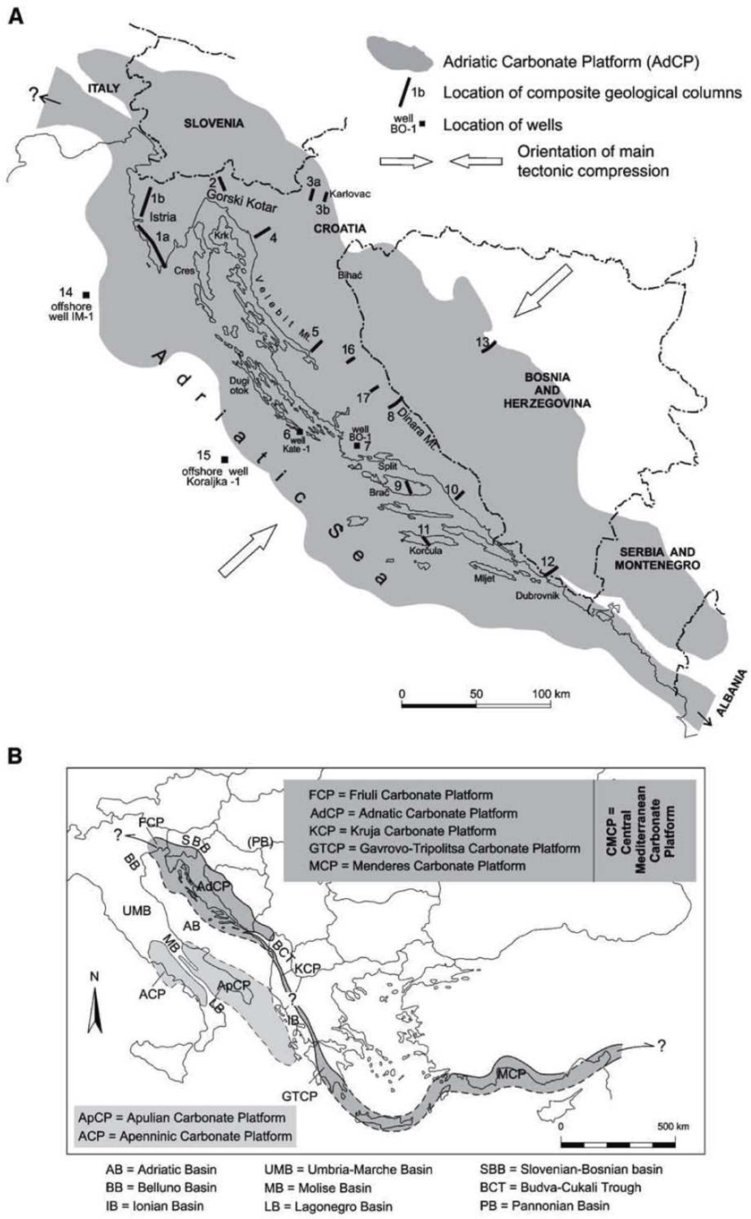


Fig. 4. A. Map outline of AdCP. B. Recent carbonate deposits in the central Mediterranean (after Vlahović et al., 2005)

The completion of AdCP deposition was characterized by regional emergence trough Late Cretaceous and the Palaeogene with synsedimentary, compressional tectonic deformations, which yielded deposition of Eocene flysch deposits in a newly formed flysch basins above either Late Cretaceous rudist rich carbonates or Eocene foraminiferal limestone. (**Fig. 1**; Vlahović et al., 2005). The final tectonic uplift of the Dinarides commenced in Late Eocene to Oligocene (Dinaric phase of the Southern Alps; see Schmid et al. 2008 for details) with formation of Outer Dinaridic thrust nappe systems, e.g., Dalmatian Zone and High Karst Unit (see **Fig. 3**) and deposition of clastic-carbonate sediments i.e., Promina marls, calcarenites, and conglomerates and Jelar i.e. Velebit carbonate breccias, and other strata that could be found in areas of Italy, Slovenia, Bosnia and Herzegovina, Montenegro, and Albania (**Figs. 1-3**).

3. Adria Microplate

The Alpine-Carpathian-Dinaridic orogenic system that encircles the Pannonian Basin System, is a part of a much larger Circum-Mediterranean orogenic system (**Fig. 5**). This orogenic system comprises tectonic units derived from paleogeographic domains of the Adriatic microplate, European continental plate and Neotethys Ocean that are incorporated into thrust systems of different polarity (Schmid et al., 2008; Ustaszewski et al., 2008). The Western and Eastern Alps, and Carpathians thrust systems face the European foreland, while the Southern Alps, and Dinaridic thrust systems face the Adriatic foreland (Ustaszewski et al., 2008).

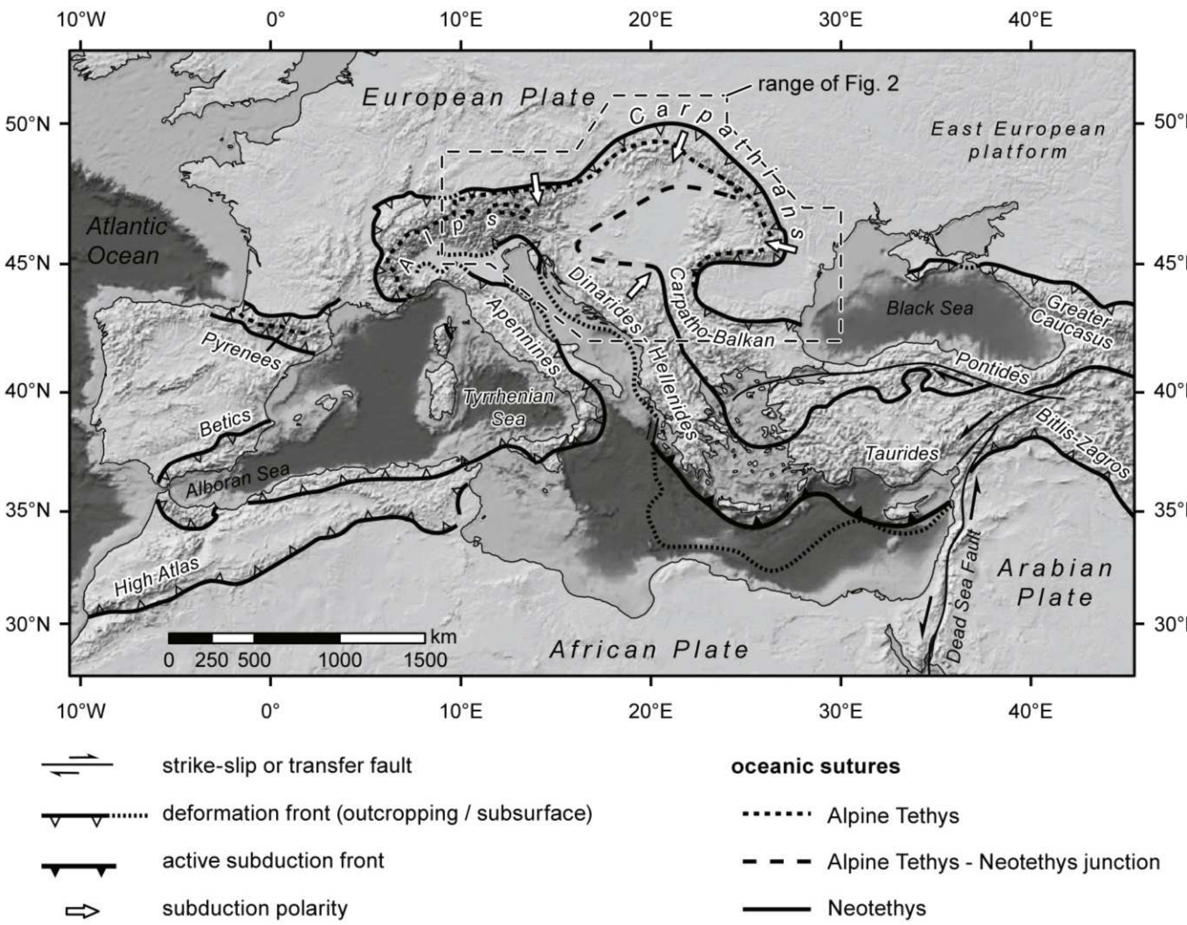


Fig 5. Circum-Mediterranean orogenic belt with the postion of present-day deformation fronts and subduction zones (after Ustaszewski et al., 2008)

This opposing structural facing is caused by change in subduction polarity between the European plate and Adriatic Microplate that is composed of Adriatic and the Apulian carbonate platforms (Schmid et al., 2008; Ustaszewski et al. 2008, and references therein). The tectonic evolution of Circum-Mediterranean orogenic systems started with the Triassic (c. 220 Ma) opening of the Neotethys oceanic embayment between the African and Eurasian Plates (**Fig. 6a,** Schmid et al., 2004, 2008). The NW part of the Neotethys, also known in literature as the Meliata-Maliac Ocean (Channell and Kozur, 1997; Stampfli et al., 1998; Stampfli and Borel, 2004, and references therein) continued to spread during the Late Triassic and Early to Mid-Jurassic. The opening of the central Atlantic Ocean initiated at the end of the Early Jurassic (Favre and Stampfli, 1992; Schmid et al., 2008) and its easternmost branches of the Alpine-Carpathian Tethys, i.e. the Piemont-Liguria and Ceahlau-Severin oceanic domains (**Fig. 6b**) led to the onset of the closure of the Neotethys in the Western Vardar oceanic domain which is evidenced by ophiolite obduction onto the eastern margin of the Adriatic Microplate (Schmid et al., 2008). Ophiolitic units obducted during the Middle Jurassic are exposed in the Central Dinaridic Ophiolite Zone of Bosnia and Herzegovina and on ”inselbergs” in NW Croatia (Mt. Medvednica, Mt. Ivanščica, and Mt. Kalnik, **see Fig. 6** e.g. in Pamić et al., 2002; Babić et al., 2002; Slovenec and Pamić, 2002; Lugović et al., 2007; Slovenec and Lugović, 2008, 2012; Tomljenović et al., 2008). According to Schmid et al. (2008), some parts of the Neotethys Ocean, the Eastern Vardar oceanic domain remained open and evolved into a back-arc basin during the Cretaceous period (**Fig. 6c**; e.g. Ustaszewski et al., 2009).

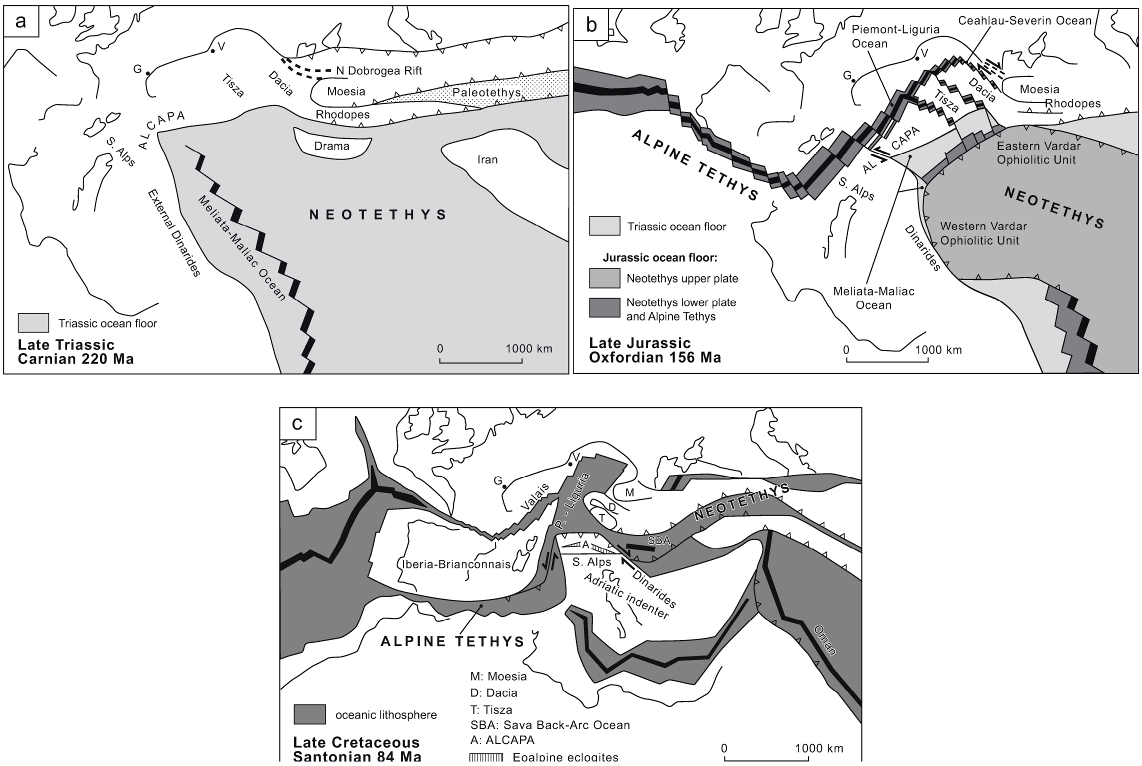


Fig. 6. Shematic palinspastic reconstruction of geodynamic evolution of European and African continents (after reconstruction presented by Schmid et al. , 2008 and references therein) visualizing distribution of oceanic and continental areas in a) Late Triassic (Carnian, 220 Ma), b) Late Jurassic (Oxfordian, 156 Ma) , and c) Late Cretaceous time (Santonian, 84 Ma).

The final closure of this paleooceanic realm commenced in the Late Cretaceous–Early Paleogene (Schmid et al., 2008; Ustaszewski et al., 2008, 2009). During the Middle Eocene and Oligocene the Eastern Vardar oceanic closure resulted in a regional E-W oriented compression leading to the westerly directed thrusting of the Tisza Mega-Unit over the Internal Dinarides (**Figs. 2** and **3**, Schmid et al., 2008; Ustaszewski et al., 2008). This tectonic event established structural relations between the tectonic units of Tisza Mega-Unit and the Internal Dinarides that are characterized by westerly directed reverse faults, and the Tisza Mega-Unit being in a higher structural position in relation to the Internal Dinarides (**Figs. 2** and **3**).

Continuous covergence between the Adriatic Microplate and the European plate in the Late Oligocene-Early Miocene (recent convergence rate between Adria indenter and Europe is ≤ 4.17 mm/yr according to Bennett et al. 2008) further resulted in the formation of thrust systems in the Alps and Dinarides (**Fig. 5;** Vlahović et al., 2005), and c. 400 km easterly directed extrusion of the ALCAPA block (including the Eastern Alps, West Carpathians and Transdanubian ranges north of Lake Balaton, see for details in Tari et al., 1999; Csontos and Vörös, 2004). The easterly extrusion of these units was mostly accommodated by the orogen-parallel transcurrent Periadriatic Fault that extended into the Mid-Hungarian Fault Zone further to the east (**Figs. 2;** e.g. Fodor et al., 1998; Tomljenović and Csontos, 2001) as a result of slab retreat of the subducted European plate beneath the Inner Carpathians and active extension of the back-arc-type in the Pannonian Basin (Royden and Horváth, 1988; Ratschbacher, 1991, Ratschbacher et al., 1991; Frisch et al., 1998; Fodor et al., 1998; Horváth et al. 2006; Cloetingh et al. 2006; Schmid et al., 2008). Furthermore, this lateral escape and extrusion affected the northern passive continental margin of Adriatic carbonate platform, i.e. Internal Dinarides (see Vlahović et al. 2005 for details) bounded by the Mid-Hungarian and the Periadriatic–Balaton lines where up to 100° of clockwise rotation recorded by paleomagnetic data (Tomljenović, 2002; Tomljenović et al., 2008) was interpreted. Consequently, structural fragments of the Internal Dinarides rotated from their original NW "Dinaridic strike" into the present day NE to E-W strike aligned with the Periadriatic and Mid-Hungarian shear zone (**Figs. 2)**.

3.1. Present day stress field in the area of Adria Microplate

Comparison of a database of earthquake focal mechanisms and slip vectors produced by a high-sensitivity seismic monitoring network, borehole breakout analysis, *in situ* stress measurement and GPS measurement data in the area of the Circum-Mediterranean and the surrounding orogens, there is possibility to address and understand the relationship between neotectonics, surface processes and recent litospheric dynamics (**Fig. 7**, Cloetingh et al., 2006; Bada et al., 2007).

The Europe-Africa subduction and collisional zones with their associated back-arc basins of the Mediterranean system represent a region of complicated short-scale stress perturbation

(**Fig. 7**, Bada et al., 2007). These horizontal stress field perturbations are caused by an active N-ward to NNE-ward directed convergence between the stable Europe and the independently moving Adriatic Microplate with convergence rates of between 3 and 4.5 mm/year (**Fig. 8**; Grenerczy et al., 2005). During the Neogene and Quaternary the Adriatic Microplate behaved as a rigid block that is considered as a main driving force for horizontal shortening and seismic activity in deformation zones along its boundaries (Anderson and Jackson, 1987; Grenerczy et al., 2005; D'Agostino, 2008; Jamšek Rupnik, 2013).

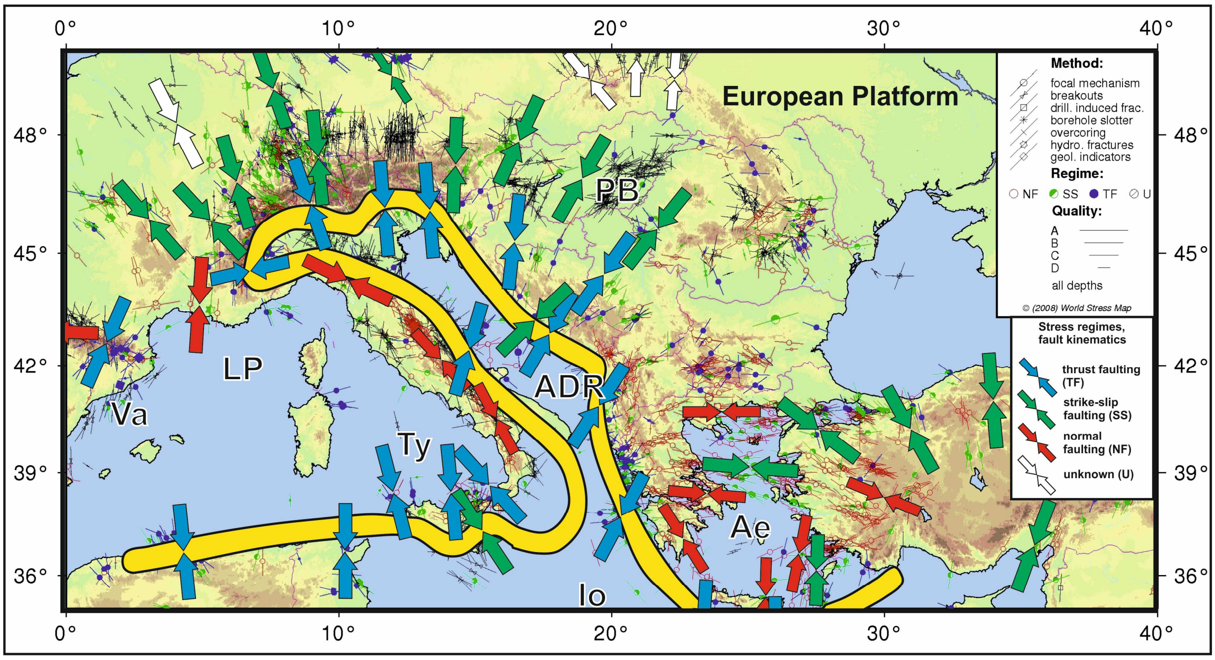


Fig. 7. Present-day maximum horizontal stress directions (Sh_{max}) and tectonic regimes in the Europe-Africa subduction and collisional zone (after Reinecker et al., 2005; Bada et al., 2007; Heidbach et al., 2008). The yellow zone indicates the Adria Microplate (ADR) boundary. Abbreviations: Ae-Aegean sea, Io-Ionian Sea, Ty-Tyrrhenian basin, LP-Liguro-Provençal basin, Va-Valencia trough, PBS-Pannonian Basin.

The total convergence between Adria indenter and stable Europe is partitioned in collisional zones of (**Fig. 8**): i) Adriatic Microplate-Eastern Alps and complementary Alpine-North Pannonian unit by 2-3 mm/yr, ii) Adriatic Microplate and Central Dinarides by 1-1.5 mm/year near shore and 2 mm/year spreading across the Dinarides, and iii) 1-2 mm/year is transferred as far-field intra-plate stresses within the weak Pannonian lithosphere (Grenerczy et al., 2000; Grenerczy et al., 2002; Grenerczy et al., 2005). Distribution of seismicity, inverted GPS site velocities, change in Euler vector, and earthquake slip vectors were used by D'Agostino et al. (2008) who suggest that the Adriatic Microplate is fragmented into a northern (Adria) and a southern (Apulia) section separated by the Gargano-Dubrovnik seismic zone (**Fig. 8).**

The Pliocene - Quaternary tectonic evolution of the AdCP and surrounding Pannonian Basin System is characterized by compression and transpression (Horváth and Tari, 1999; Dolton, 2006), whereas build-up of intra-plate stresses within the Pannonian lithosphere is associated to the present NE-ward translation and counterclockwise rotation of the Adria Microplate that converged with the Alpine orogenic belt (**Fig. 8**; Gerner et al., 1999; Márton et al., 2003; Márton et al., 2005; Grenerczy et al., 2005; Pinter et al., 2005; Jarosinski et al., 2006; Ustaszewski et al., 2008; Jarosinski et al., 2011). According to Bada et al. (2007) and Jarosinski et al. (2011) this is caused by complete consumption of the subducted lithosphere of the European foreland and the detachment of the subducting slab in the Carpathians ultimately caused the PBS to become locked and subjected to a compressional stress field with varying stress orientations.

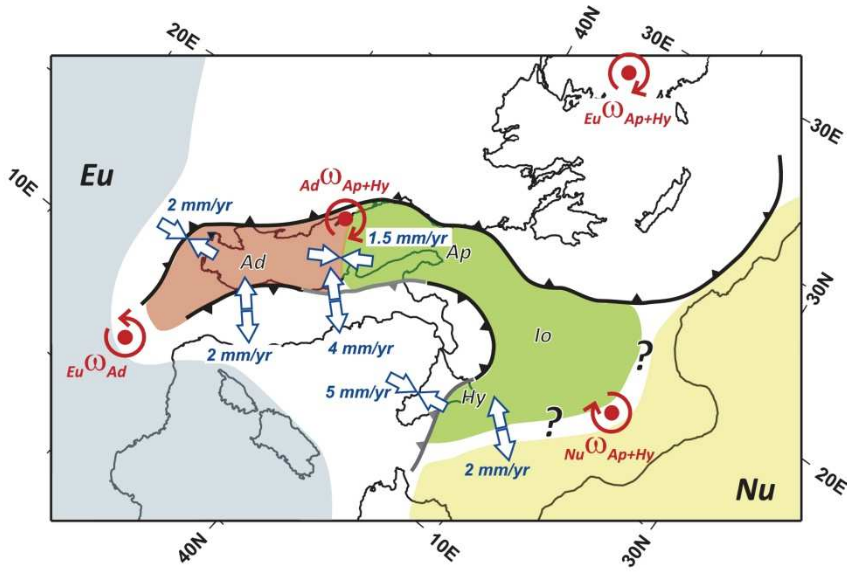


Fig. 8. A) GPS velocities with respect to Eurasia (after D'Agostino et al. 2008).

The Euler pole of the counterclockwise rotating Adriatic Microplate located in the Western Alps by e.g. Anderson and Jackson (1987), Calais et al. (2002), Oldow et al., (2002) has been confirmed by Weber et al. (2010) as 45.03°N and 6.52°E (**Fig. 8**, pole GPS-17) that is furthermore characterized by angular velocity vectors of 0.297 ± 0.116°/Ma. Besides those stresses that directly propagate from Adria through the Dinarides far into the PBS, the significant stress transfer occurred due to "Adria push" that was achieved by dextral strike-slip motions and pure thrusting south of the Periadriatic Line and Mid-Hungarian fault zone. This process resulted in the Pliocene and Quaternary structural inversion of the inherited structural trends in the PBS (Grenerczy et al., 2005; Reinecker et al., 2005; Bada et al., 2007; D'Agostino et al., 2008; Jarosinski et al., 2011; Jamšek Rupnik, 2013).

The present-day horizontal stress pattern (S_{Hmax}) in the PBS is shown by heterogeneous stress indicators, mainly through borehole breakout and fault plane solutions data, which suggest that the alignment of compression and the trend of the principal maximum stress axis changes gradually from NNW-SSE to N-S in the Southern, central - Eastern Alps, respectively, and finally into NNE - SSW to NE - SW in the Dinarides and SW part of the PBS (**Fig. 9**; Bada et al., 1999; Bada et al 2007; Herak et al., 2009).

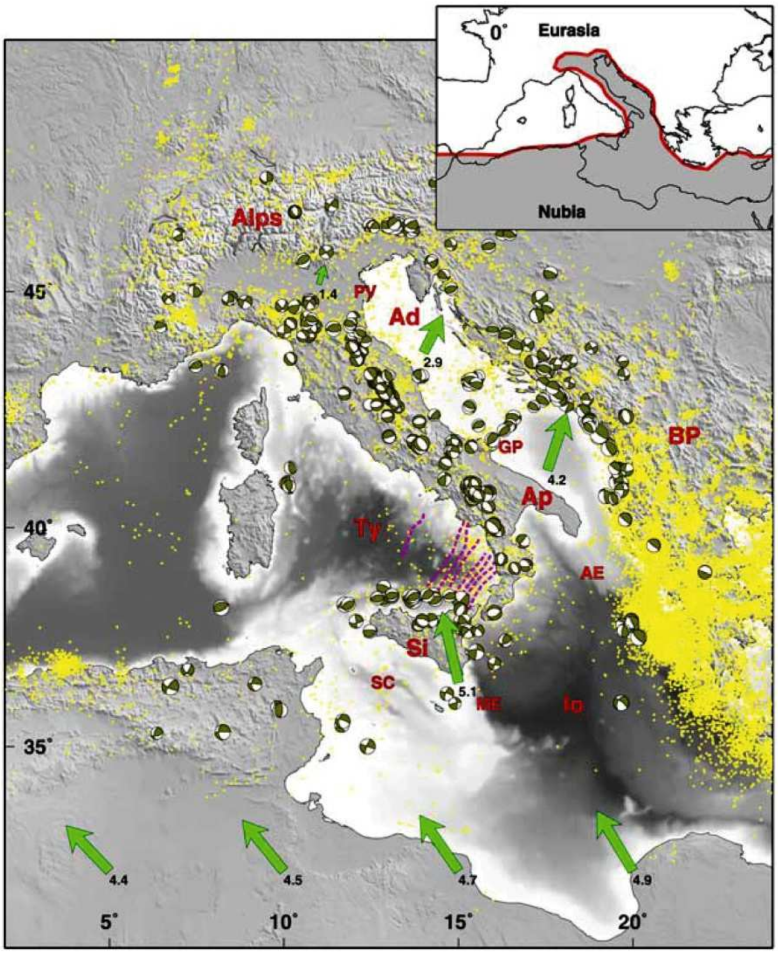
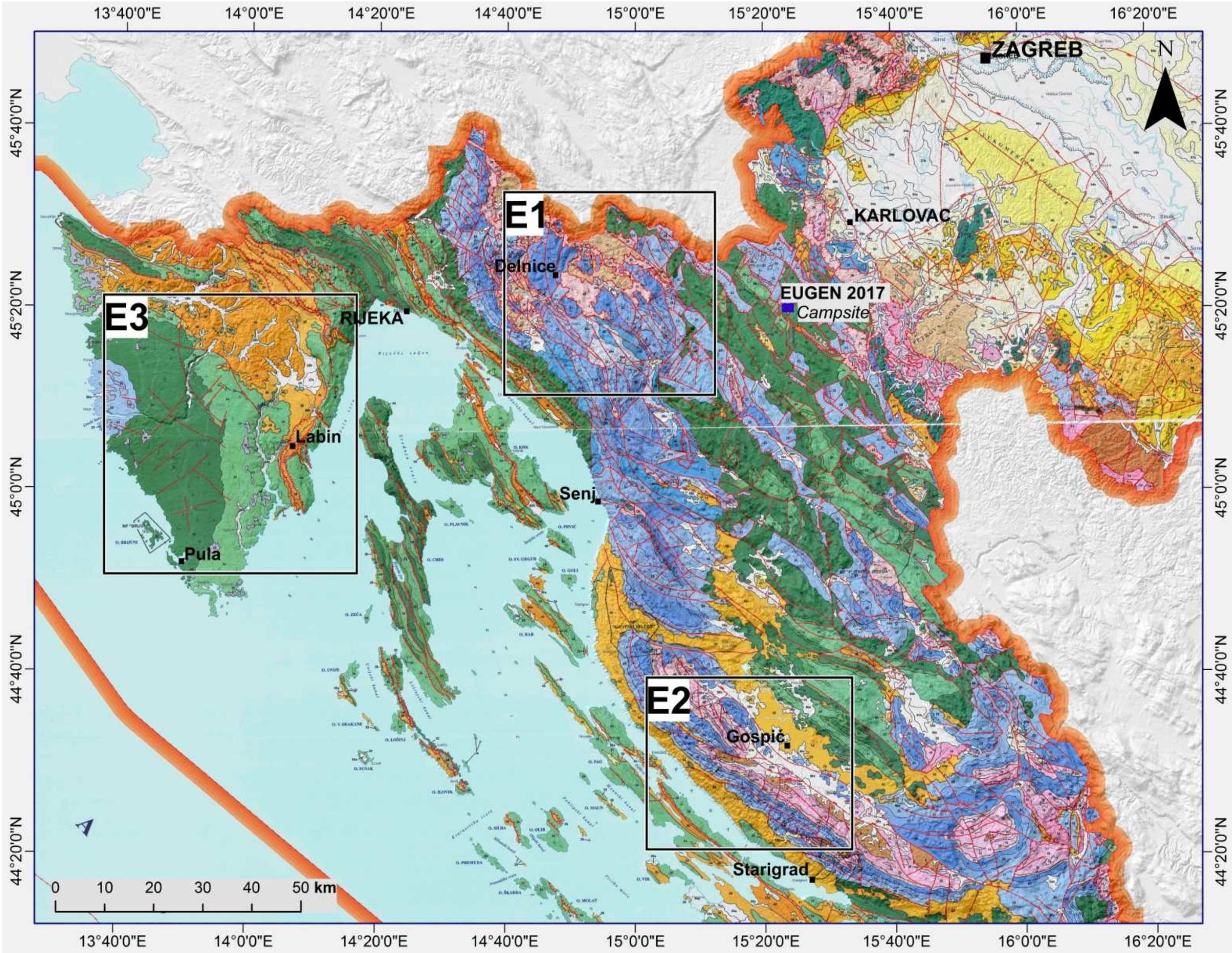


Fig. 9. Seismotectonic settings of circum-Adriatic area with topography, seismicity and earthquake focal mechanisms taken from Pondrelli et al (2006) from perod between 1973-2006 (http://neic.usgs.gov). Green arrows represents GPS velocities in mm/a relative to Euroasia. Abbrevations: Ad-Adriatic Sea; Ap-Apulia; AE-Apulia Escarpment; BP-Balkan Peninsula; GP-Gargano Promontory; Io-Ionian Sea; ME-Malta Escarpment; PV-Po Valley; Si-Sicily; Sc-Sicily Channel; Ty-Tyrrhenian Sea (after D'Agostiono et al., 2008).



Geological map of Croatia (CGS, 2009) with indicated EUGEN 2017 Campsite and selected excursion locations.

EXCURSION—E1

Excursion leader: Marin Sečanj, mag.geol.ing.

Skrad, Gorski kotar

Significant Landscape of Devil's Passage and the Green Whirlpool

Introduction

Significant landscape of Devil's Passage and the Green Whirlpool is located in NW part of External Dinarides, in the hilly Gorski kotar area, within Skrad municipality. Due to diversitiy of geomorphological features, the area of Devil's Passage and the Green Whirlpool was protected and classified in the 1962 as the Geomorphological reserve and today it has the status of a Significant landscape. According to Koch (1931) and Savić & Dozet (1984, 1985), the wider Skrad area is built of: 1) Permian sandstones, shales and conglomerates, 2) Upper Triassic clastics and Haubtdolomite and 3) Lower and Middle Jurrasic limestones and dolomites. Many authors debate over presence of Lower Triassic deposits in the Gorski kotar area, while they all agree that the lack of presence of Middle Triassic deposits is caused by emersion (Đurđanović, 1967, Babić, 1968, Šćavničar, 1973, Savić & Dozet, 1985, Aljinović, 1997). The recent structural relations between the litostratigraphic units in the Gorski kotar area are complex. One group of authors (e.g. Savić & Dozet, 1985) encoruage the theory that the Gorski kotar area is autochtonous, where only smaller structural blocks are allochtonous. Contrary to that, Herak (1980) describes three allochtonous tectonic megaunits, with nappe system covering most of the Gorski kotar area.

According to Gudac (2014) and Sečanj (2014), the area of Significant landscape of Devil's Passage and the Green Whirlpool is built out of litostratigraphical units of: Permian clastic rocks (shales, sandstones and conglomerates); Triassic red-green clastic rocks alternating with dolomites; Triassic massive dolomite („Main dolomite"); Lower Jurassic dolomites and limestones, Lower Jurassic fossiliferous (gastropod-bivalve-brachiopod) limestones and Lower Jurassic bioturbated („spotted") limestones (**Fig 10a**). Structural relations between the litostratigraphic units are complex due to three tectonic phases. The oldest phase is characterised by thrust faulting that resulted in allochthonous (nappe) position of Permian and Triassic deposits above autochthonous Triassic and Jurassic deposits. The second phase is characterised by extension accommodated by normal faulting, which resulted in breaking apart of the nappe contact and opening of tectonic window located in the canyon of Curak and Jasle streams (**Fig 10a and c**). The last tectonic phase is characterised by reverse faulting that enabled uplift of the autochthonous Norian and Rethian Hauptdolomite in structural position above lower Jurassic carbonates. In the description of each excursion stop, all litostratigraphic units are described shortly. Details about the carbonate succsession of the External Dinarides will be given in excursion to Mt. Velebit.

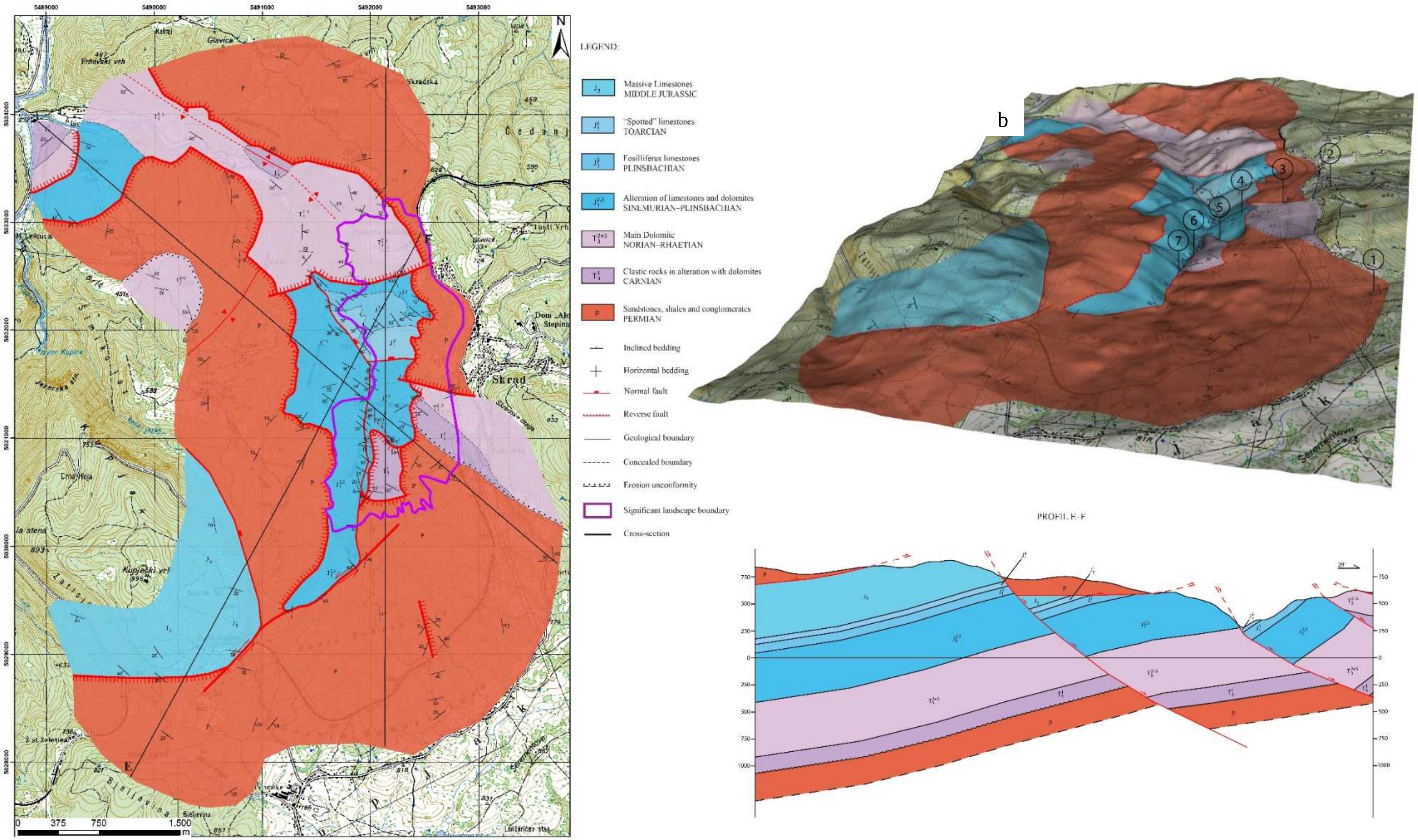


Fig. 10. (a) Geological map of wider Skrad area, (b) excursion stops visualized on the geological map overlayed on 20x20 m DEM, (c) geological cross-section of the area (modified after Sečanj, 2014).

c

a

Stop 1: *(Permian clastics and nappe tectonics)*

Permian clastic rocks are the oldest and the most widely spread deposits in the wider Skrad area. Due to increased weathering and unpermeability they are mostly covered with vegetation and only partly visiable in road cuts, gullies and ditches. These deposits are built out of rythmical sandstones, shales and conglomerates sequences (**Fig. 11a**). Sandstones are composed of quartz and muscovite and only partially of feldspars, whereas shales are composed mostly of feldspars, fine grained quartz, and muscovite. In some parts, foliation can be seen in shales and it is marked by plane-parallel orientation od muscovite and quartz graines. Conglomerates are built of coarsed-grained quartz floating in fine-grained matrix.

Permian clastic rocks mostly build the hanging wall of a large thrust sheet in the area, whereas, pressumably, shales represented the low friction material required for the development of the decollement horizon. The thrust contact between the Permian clastic rocks in the hanging wall and younger carbonate deposits in the footwall is only visiable in few ditches and sinkoles along subhorizontal fault plane (**Fig. 11b**).

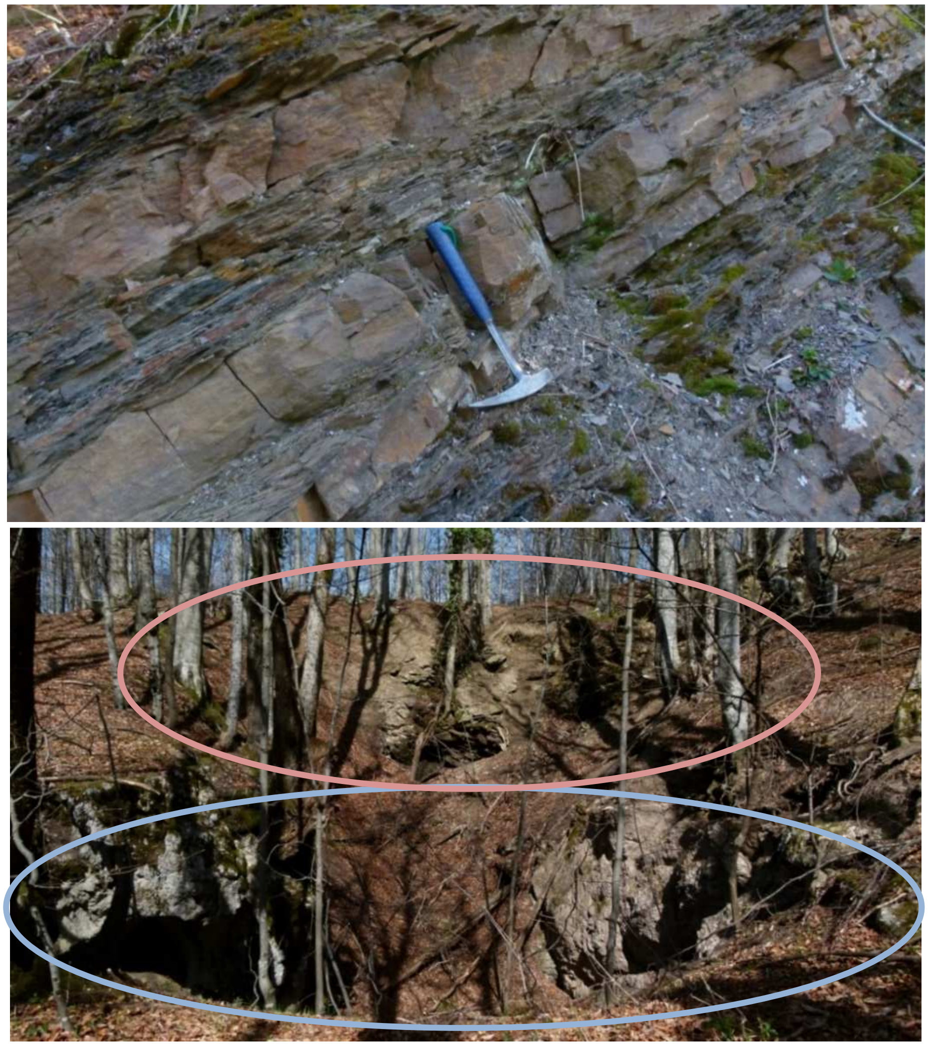


Fig. 11. a) Outcrop of the Permian sandstones and shales (upper photo) and b) thrust contact between the Permian clastic rocks in the hanging wall and younger carbonate deposits in the footwall (bottom photo).

Stop 2: *(Source of the river Dobra – Upper Triassic clastics and carbonates)*

The second largest river in the Gorski kotar area, the River Dobra, emerges from several minor sources. One of them is located near the centar of Skrad, at the tectonic contact between Permian shales and sandstones and Upper Triassic mudstones, siltstones and dolomites. Clastic deposits of Upper Triassic differ in color, grain size and mineral composition from the Permin deposits in the area. Carnian clastic deposits are presented with redish and greenish mudstones, siltstones and fine-grained sandstones (**Fig. 12a**) which are composed of abundance of feldspar, quartz, however, in contrast to Permian clastics there is a complete lack of mica. In the upper part of Carnian deposit sequence there is an increase in the amount of carbonate component which reflects in the alteration of clastics deposits with dolomites (**Fig. 12b**) Norian-Rhaetian carbonate deposits are presented with vertical alteration of early-diagenetic and late-diagenetic dolomites with stromatolite lamination (**Fig. 12c and d**).

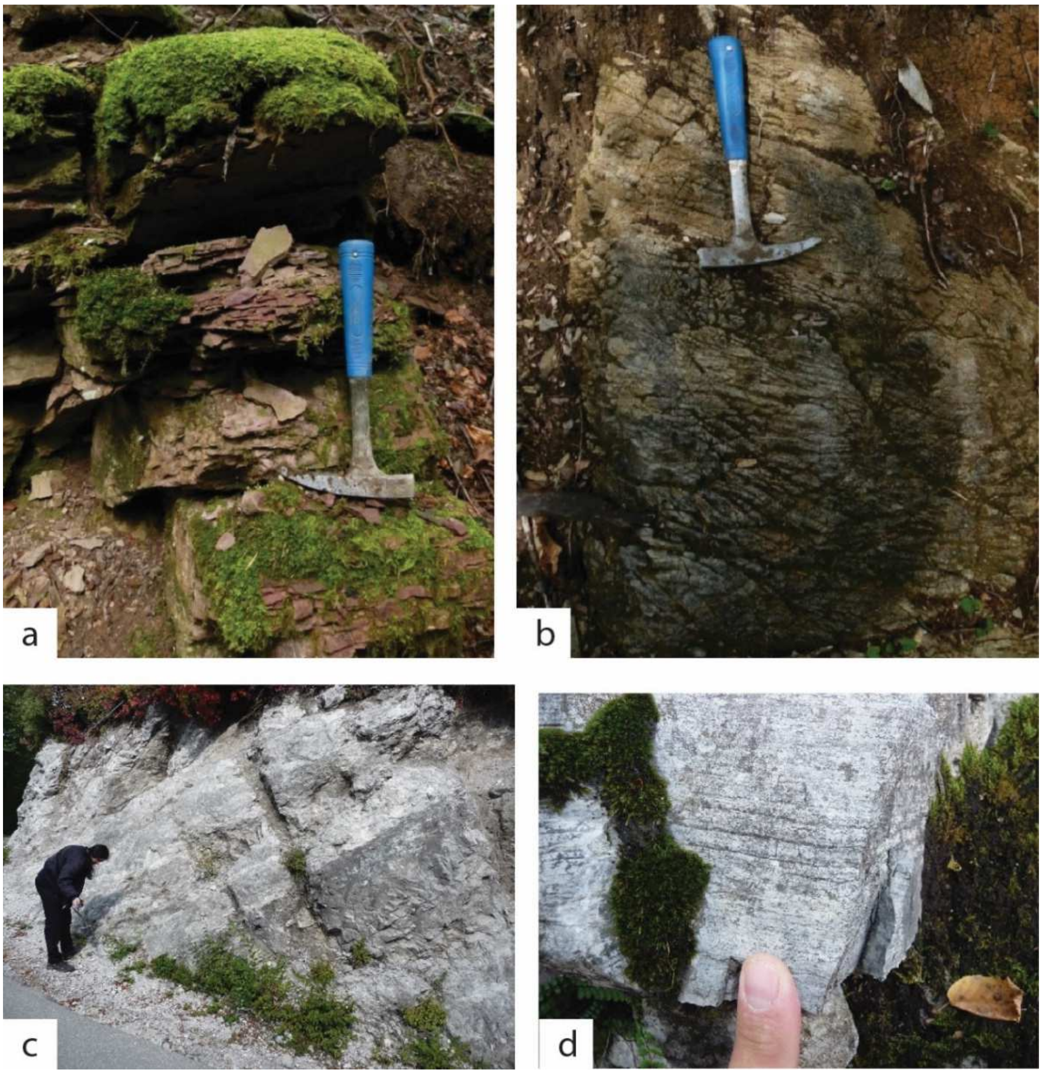


Fig. 12. Outcrops of (a) Carnian clastics, (b) Carnian dolomites, (c) Norian–Rhaetian Main Dolomite with (d) stromatolite lamination.

Stop 3: *(Reverse faulting – the youngest tectonic phase)*

Near the railway station in Skrad there is a clearly visiable contact between Permian clastics and Upper Triassic Carbonates. This contact is along reverse fault, where Permian conglomerates and shales build the hanging wall, while allochotnous Norian-Rhaetian Main Dolomite build the footwall of the fault (**Fig. 13**). Simmilary orientated fault is located on the nearby local road along which autochtonous Norian-Rhaetian Main Dolomite is located in a structural position above younger Lower Jurrasic carbonates. Generally, these reverse faults have a E-W strike with the tectonic transport top to south. Also, in the Main Dolomite reverse faults with the same strike, but with the tectonic transport top to North have also been determined (**Fig. 13**). Because of the same type of movement and same strike, these faults represent conjugated couples and belong to the same tectonic event with the main compression axis striking N-S. Due to the relative position of these faults in relation to the previously mentioned thrust sheet and extensional tectonics in the area, it seems that this reverse faulting represent the youngest tectonic phase which took part in the formation of the Significant landscape of Devils Passage and the Green Whirlpool.

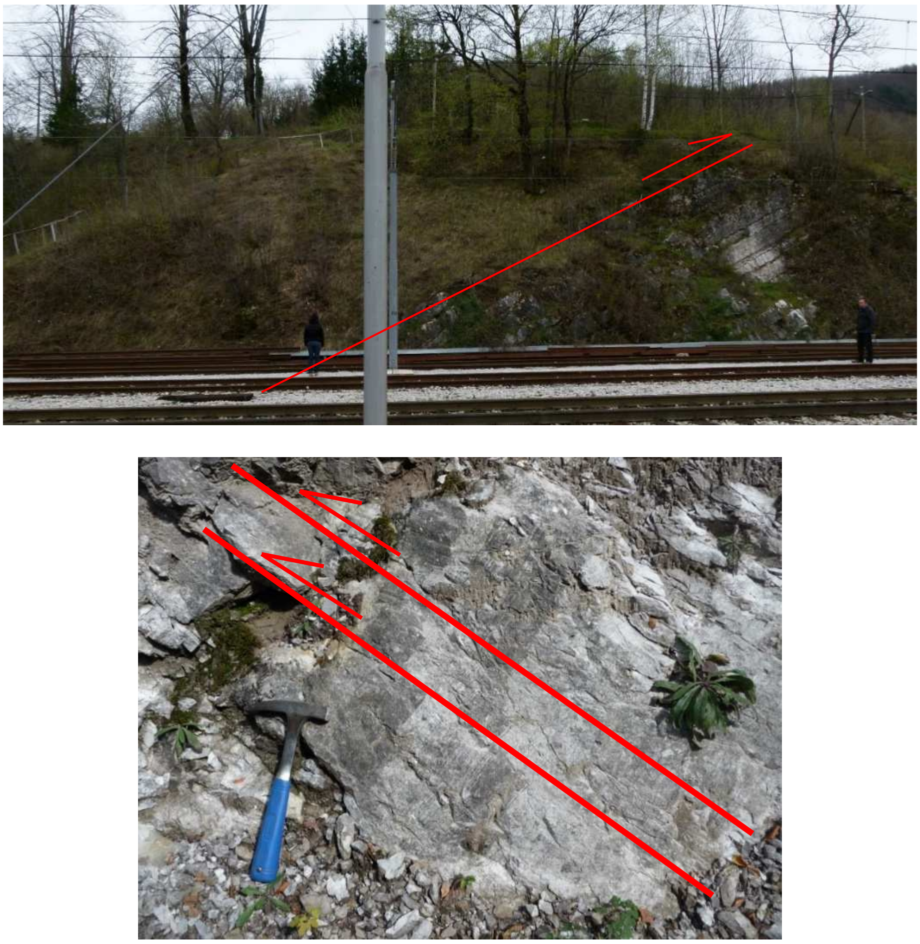


Fig. 13. Tectonic contact along reverse fault, where Permian clastics build the hanging wall, while Norian-Rhaetian Main Dolomite build the footwall of the fault (upper photo) and conjugated couples belonging to the same tectonic event in the Upper Triasic Main Dolomite (bottom photo).

Stop 4: *(Lower Jurassic Carbonates and Curak canyon folds)*

Lower Jurassic carbonates build the majority of stream Jasle and Curak canyons and the sorounding cliffs. They consist of following litrostratigraphic units: 1) Sinemurian and Plinsbachian alteration of Limestones and Dolomites, 2) Plinsbachian fossiliferous limestones and 3) Toarcian bioturbated („spotted“) limestones.

Sinemurian–Plinsbachian vertical and horizontal alteration of limestones and dolomites can be easily recognized in the area by well defined bedding planes, where thickness of layers varies from 20-180 cm (**Fig. 14a**). The age of this unit is defined by appearance of *Lituosepta recoarensis* foraminifera in limestones (**Fig. 14b**). Dolomites are mostly late-diagenetic with the apeareance of cyanobacterial laminas in some parts (**Fig. 14c**). Plinsbachian fossiliferous limestones represent an 80 m thick sequence with abundance of macroscopic fossils of Lithiotides, Brachiopodes and Gastropods (**Fig. 14d**). This sequence represents a transition between alternating limestones and dolomites in the bottom and bioturbated limestones in the top most part of the Lower Jurrass Carbonate sequence.

Fig. 14. (a) Outcrop of well-bedded Sinemurian–Plinsbachian Limestones and Dolomites, (b) appereance of *Lituosepta recoarensis* foraminifera in Sinemurian–Plinsbachian limestones, (c) apeareance of cyanobacterial

laminas in dolomites, (d) macroscopic fossils of Lithiotides, Brachiopodes and Gastropods found in Plinsbachian fossiliferous limestones and (e) outcrop of Toarcian bioturbated („spotted“) limestones.

Toarcian bioturbated („spotted“) limestones present the upper most part of Lower Jurrasic carbonates. They can only be found on the local road above the Curak stream and in the Curak stream canyon itself. „Spotted“ limestones represent intensively bioturbated mudstones with high clay content. Limestones are well-bedded with the maximal thickness of layers around 20 cm (**Fig. 14e**).

The contact of Lower Jurassic carbonates with older, Triassic and Permian deposits is entirely along faults. Most often these deposits are situated in a tectonic window, i.e. they represent the autochtonous deposits in the footwall of the previously mentioned nappe. Lower Jurassic Carbonates are marked by numerous decametric folds which are visiable along the steep cliffs above the stream Curak (**Fig. 15**). Due to their chaotic positioning, irregularity of orientation and unconnectivity to the surrounding layers, it is presumed that these folds represent slamp folds formed by submarine gravitational slides.

Fig. 15. Photos of decametric recumbent folds that can be seen in stream Curak canyon.

Stop 5: *(The Green Whirlpool)*

The Green Whirlpool represent a Karst spring situated in a "half-cave" beneath a 70-m high cliff built of Sinemurian–Plinsbachian alteration of Limestones and Dolomites. High discharge at the spring, and its high hydropotential, is used for power plant „Munjara" built in 1921. The reason for the high discharge at the spring is because of underground drainage through system of caves, pits and cracks of a much larger area. Karst spring itself is formed in the position of a collapsed cave (**Fig. 16a**). The reason for the water to reach surface here is because of a fault that acts like a barrier which stops the underground flow of the water. Because of that, water flows along the fault until it reaches the surface. This fault represents the contact between the carbonates in which we can see previously mentioned folds and underlying carbonates in the Curak stream of complitelly different orientation (**Figs. 16b and c**).

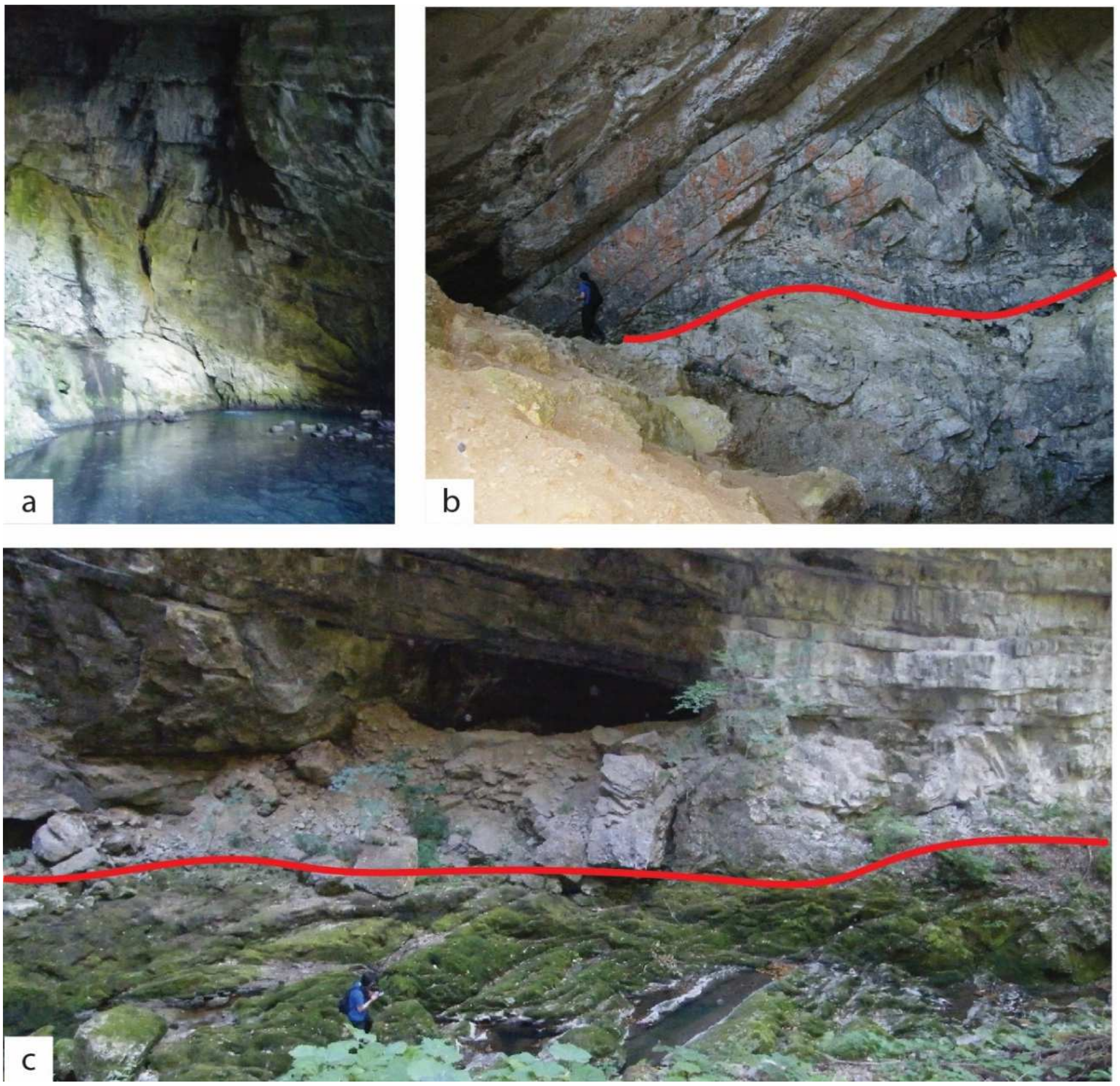


Fig. 16. (a) Photo of the karst spring named Green Whirlpool, (b) tectonic contact in the "half-cave" next to the karst spring and (c) contact along fault between the carbonates in which we can see folds and underlying carbonates in the Curak stream of complitelly different orientation.

Because of very pronouncedly folding, where most folds are recumbent, with often lateral discontinuitation between neigbouring folds, it is not completely clear mentioned discordant contact (**Fig. 16b and c**). At the Green Whirlpool karst sprin it seams that this contact represent fault with a low dip angle created by differentional shear between the folds limbs or it is a regional decollement horizon, along which larger structural blocks are divided. In the vicinity of the Green Whirlpool there is 70 m high waterfall, that is very strange because we expect that all surface water should be transported through the underground channels into the karst spring. The reason for this could be associated with water flow on top of the impermeable Permian and Triassic clastic rocks which can not sink until it reaches the cliff over which it gushes next to the spring (**Fig. 17**).

Fig. 17. Photo of the waterfall gushing next to the Green Whirlpool spring with clearly visible fold next to it.

Stop 6: *(Formation of the canyon and normal faulting)*

Beside the forementioned nappe tectonics and reverse faulting, extension accommodated by normal faulting had a major role in structural-geological setting of the area. These faults are younger than the nappe and the result of it is in breaking apart of the nappe contact and opening of tectonic window located in the canyon of Curak and Jasle streams.

So, what is the full story behind the formation of this canyon? In the beginning, after nappe tectonics took place, the rainfall water drained toward the main recipient (a stream or a river) because of the impermeabile clastic deposits on the surface (**Fig. 18a**). Due to extensional tectonics, cracks and faults are opening and Lower Jurassic carbonates become exposed to weathering. Surface water infiltrates through the cracks and underground water flows are starting to form (**Fig. 18b**). Water slowly erodes clastic and carbonate deposits, both mechanically and chemically. Because of the advance of erosion and the existence of suitable conditions, the main surface water flow is beginning to form (Jasle and Curak stream) in the lowest part of the terrain. The stream receives its water from underground water percolating from carbonates and from occasional surface waters flowing towards the stream. With the deepening of the streambed, because of the carbonate rock erosion, the canyon starts to form. (**Fig. 18c**).

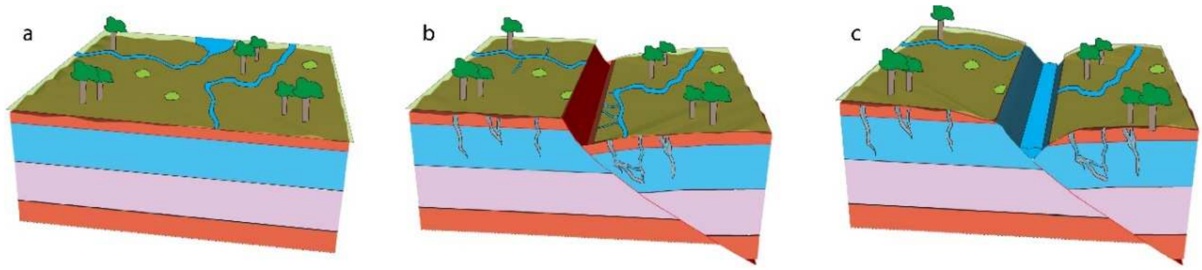


Fig. 18. Schematic overview of the formation of the stream Curak and Jasle canyon where: (a) represents the faze after nappe tectonics took place, (b) initial faze of opening after extensional tectonics and (c) final phase after weathering.

One of the most important normal faults is the one that strikes N-S, along the canyon of Curak and Jasle streams, with the tectonic transport to the east (**Fig. 19**). Because of the spatial postiton of the fault and its outline in the morphology of the canyon (**Fig. 19**), it is presumed that the formation of the canyon is predisposed by this fault and by incision of the stream along the fault zone.

Fig. 19. Fault plane of a normal fault in the stream Jasle canyon.

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Stop 7: (Muževa Hiža Cave)

Caves and pits are speleological objects that differ from each other depending on a dip of the channels. Caves mostly have horizontal channels while pits channels are vertical. Muževa Hiža cave is located at the end of Devils Passage that is opened for tourists. The dimension of the Muževa hiža Cave entrance is around 40 x 15 meters and total length from the entrance to the lake is around 130 meters (**Fig¸. 20**). The entrance of Muževa Hiža cave (**Fig. 21**) was formed in the Sinemurian and Plinzbachian limestones and dolomites, presumablly by the collapse of the core of a fold due to chemical and mechanical weathering. The cave itself has only a few of speleothems, which are formed by crystallization of the calcium carbonate mineral.

At the end of the Muževa Hiža cave there is a lake and in it there are two boats (**Fig. 21**), dating back to the 19th century. Why are they there and who brought them is still a mystery.

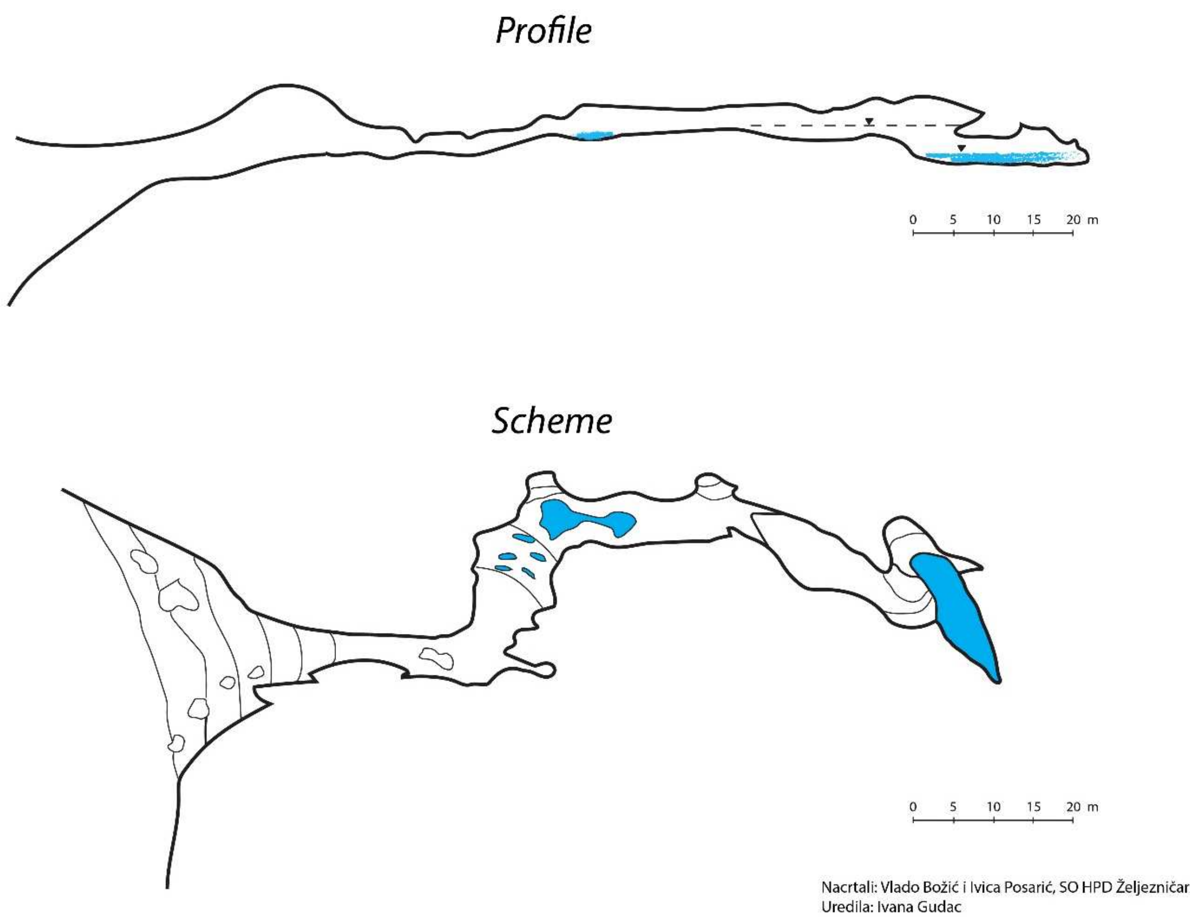

Fig. 20. Profile and scheme of the Muževa Hiža cave (original schematics by Vlado Božić and Ivica Posarić, SO HPD Željezničar; edited by Ivana Gudac)

Fig. 21. Photos of the entrance of the Muževa Hiža cave (upper photo) and of the two boats at the end of the cave (bottom photo).

EXCURSION--E2

Excursion leaders: Asst. Prof. Bojan Matoš, PhD; David Rukavina, mag. geol.

Mt. Velebit

Insights in the sedimentary and tectonic evolution of Dinarides

Introduction

Mt. Velebit is mountain range that streches from Senjska Draga (NW) to Zrmanja River (SE) with length of 150 km and 14 km average width (Velić, 2007a). With an area of 2280 km^2 Mt. Velebit is the longest and the wides mountain range in Outer Dinarides (Velić, 2007a). The Mt. Velebit as a part of fold and thrust belt of external Dinarides was formed by a thin-skinned Cenozoic thrusting of eastern Adriatic plate margin (e.g. Blašković, 1998; Tari, 2002; Tari Kovačić and Mrinjek, 1994; Schmid et al., 2008; Korbar, 2009; with references).

Considered to be *locus typicus* of karst landscape and morphology, Mt. Velebit is almost completely built from sedimentary rocks, reaching up to 8000 m. Mt. Velebit is composed of (**Figs. 1** and **22**; Tari Kovačić and Mrinjek, 1994; Velić, 2007 with references):

i) continous Late Paleozoic (Carboniferous and Permian) clastics that represent alteration of shales, sandstones (*e.g., Brušane Sandstones/Siltites*), quartz conglomerates (*e.g., Košna Conglomerates)* and shallow marine carbonates (*e.g., Schwagerina -Mizzia Dolomite)*,

ii) Mesozoic clastic and carbonate successions (*e.g., Middle to Late Triassic clastic layers, Middle to Late Triassic carbonate formations, Jurassic and Cretaceous carbonate formations),*

iii) Paleogene transgressive and regressive clastic and carbonate megasequences *(e.g., Eocene Foraminiferal Limestones and Flysch Deposits, and Promina Conglomerate and Velebit (Jelar) breccia formations), and*

iv) Quaternary glacio-fluvial, fluvial and gravitational deposits.

The tectonic arhitecture of Mt. Velebit characterize an asymmetric anticline (**Fig 10**) that is multiple faulted, where SW limb is characterized by homocline and strata deeping towards SW, whereas NE limb is reduced by NW-striking Lika Fault. Most of the important tectonic contacts and fault zones are however covered by Eocene-Oligocene Velebit breccia, which resulted in ambigous structural interpretations. Accordingly, tectonic evolution of Mt. Velebit is explained by two possible case scenarios.

In first case, according to Bahun (1974) and Prelogović et al. (1995, 2004) Mt. Velebit is uplifted in a hangingwall of NE-dipping reverse Velebit fault that strikes along the Mt. Velebit's coastline and is recent covered by the carbonate breccia (i.e., Jelar or Velebit breccia; Bahun, 1963; Vlahović et al., 2012), whereas in second scenario Korbar (2009) indicated Mt. Velebit anticline as a positive flower structure formed along the Cenozoic transpressive, dextral-reverse fault (**Fig. 23**).

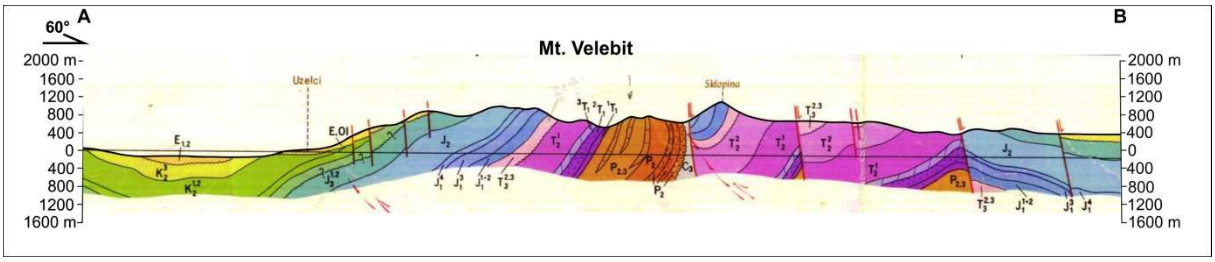

Fig. 22. Geological profile of Mt. Velebit (after Sokač et al. 1974). See **Fig. 13** for profile location. Legend: $\mathbf{C_3}$- Carboniferous shale, conglomerate and andstone; $\mathbf{P_2}$-Middle Permian sandstone; $\mathbf{P_{2,3}}$-Middle-Upper Permian dolomite; $^{1,2,3}\mathbf{T_1}$-Middle-Uppermost Lower Triassic dolomites with terrigenous clastics; $\mathbf{T_2^1}$- Anisian limestone and dolomite with clastic intercalations; $\mathbf{T_3^{2,3}}$- Upper Triassic dolomite; $\mathbf{J_1^{1+2}}$- Lowermost Jurassic limestone, subordinate dolomites; $\mathbf{J_1^3}$- Middle Lower Jurassic limestones; $\mathbf{J_1^4}$- Uppermost Lower Jurassic limestones and subordinate dolomites; $\mathbf{J_2}$- Middle Jurassic limestones and dolomitized limestones; $\mathbf{J_3^{1,2}}$- Upper Jurassic limestones; $\mathbf{K_2^{1,2}}$- Upper Cretaceous (Cenomanian-Turonian) limestones and dolomites; $\mathbf{K_2^3}$- Upper Cretaceous (Santonian) limestones; $\mathbf{E_{1,2}}$- Eocene foraminiferal limestone dolomite; **E,Ol-** Eocene, Oligocene limestones, conglomerates and breccias (Velebit breccia).

Fig. 10.

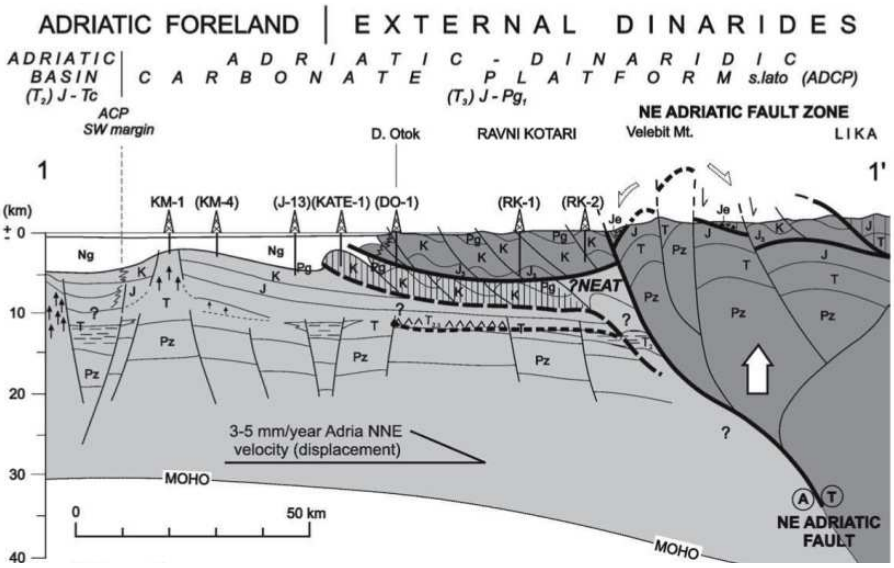

Fig. 23. Recent structural arrangement of the External Dinarides in the central portions of Dinarides. (after Korbar, 2009).

With respect to the completeness of sedimentary succession of the Late Paleozoic, Mesozoic, and Paleogene formations that are best exposed in the southern part of Mt. Velebit, going along the road from hinterland i.e., Lika region (town of Gospić), across the Mt Velebit (Baške Oštarije pass) towards the Adriatic coastline (town ofKarlobag) our profile will cover mainly Late Paleozoic, Triassic and Jurassic clastic and carbonate successions, and Paleogene, i.e., Late Eocene Velebit (Jelar) carbonate breccia deposits. With twelve geological stops (**Fig. 24**) along the tour, the total tour length is c. 32 km, with elevation difference of 386 m. The maximum height will be achieved at the Kubus (Baške Oštarije pass) at elevation of 968 m.

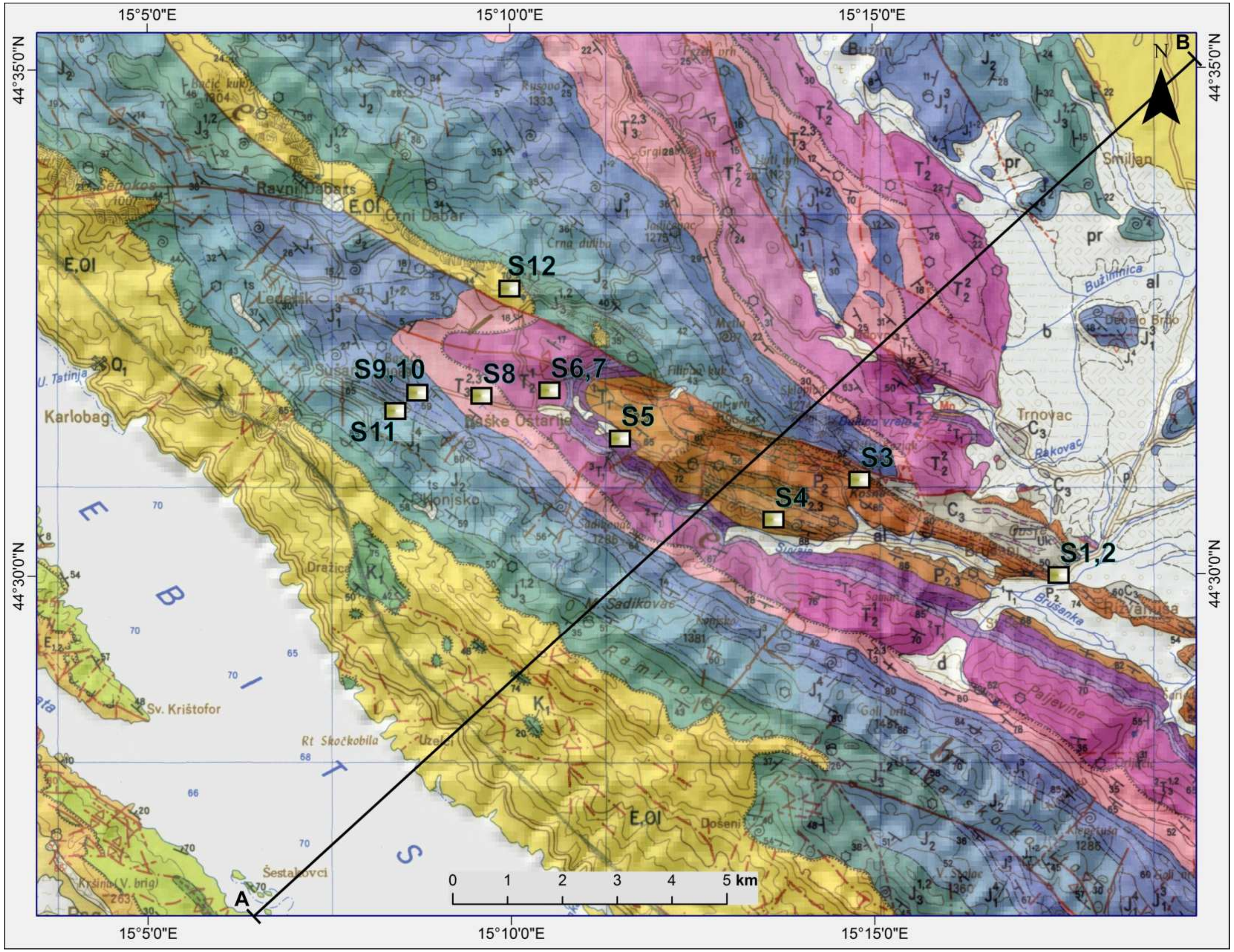

Fig. 24. Geological map of central Mt. Velebit area (after Sokač et al., 1974) with numbered geological stops along the road Rizvanuša - Karlobag. Geological profile A-B is ilustrated in **Fig. 22.**

Stop 1: *(Rizvanuša)*

Carboniferous shales, sandstones and conglomerates

This stop is located in vicinity of village Rizvanuša, just at the foothills of Mt. Velebit. Here we will see Upper Carboniferous succession of shales, sandstones and conglomerates. Upper Carboniferous age of sandstones and shales is defined on numerous index microfossils, in studys of Kochansky-Devidé (1955, 1959, 1964), from which most important are: *Velebitella siplex, Tricites pseudosimplex, T. pusillus, T. salopeki, T. brevispara, Anthracoporella spectabilis, A.vicina, Archeolithopyllnum missouriensum, Tubretina sp,* and others. Shales contain quartz, micas, plagioclase, pyrite and organic matter (**Figs. 25** and **26**). Sandstones are defined as quartz wacke or lithic wacke, mainly fain grained and good sorted. Clasts contain quartz, mica, chlorite, little plagioclase, lithic and organic component, while the matrix is chlorite-sericite (Sokač et al., 1976). Conglomerates appears as a lenses within dominant sandstones and are stratigraphically determined by their position in relation to sandstones and shales Fig (). They contain clasts mostly of quartz, chert and in less presence tuff and shales. Clasts are moderately sorted with psamitic matrix with the same content (Sokač et al., 1976).

Fig. 25. Carboniferous shales in Rizvanuša village.

Fig. 26. Carboniferous shales and conglomerates in Rizvanuša village.

Stop 2: *(Brušane)*

Middle Permian "Brušane Sandstones"

Outcrops of Brušane sandstones can be found on Gospić – Karlobag road in Brušane village. Fossil content in them was never found, but their stratigraphic affiliation is concluded from normal boundary to carbonate succession of Middle and Upper Permian. Sandstones are medium to coarse grained wacke, with quartz, lithic, feldspars, mica and chlorite clasts. Matrix is chlorite-sericite. Varieties, which have more carbonate cement, are defined as sub-wacke and they are more common in upper stratigraphic part of unit, close to transition to Middle Permian carbonates. Brušane sandstones (**Fig. 27**) are distinguishable with their red-brown color, which is consequence of later oxidation of unstable minerals, such as ferrous iron in carbonates and pyrite. Presence of these minerals point towards the reductive conditions of sedimentation. Alongside with this, autigenic complex minerals of matrix (chlorite-sericite-illite) suggests marine environment, which was rich with Mg and K – ions and enabled reconstitution of terrigenous material into stable minerals. Heavy fraction in this sandstones is mostly made of zircon, tourmaline and rutile, less of apatite and as accessory garnet, titanite, epidote and others (Sokač et al., 1976).

Fig. 27. Middle Permian Brušane sandstones along Gospić – Karlobag road.

Stop 3: *(Košna spring in the vicinity of Brušane)*

Permian "Košna" conglomerates

Košna conglomerates are located around the Košna spring in vicinity of village Brušane. Microfossil remains are found inside the individual clasts, among which are noticed Carboniferous and Lower Permian limestone rocks. Since these conglomerates, somewhere lies transgressive over Carboniferous or inside the Brušane sandstones whit whom they exchange vertically and laterally, they are stratigraphically defined as Middle Permian. Mostly they are thick bedded and looks bulky in the outcrops.

Typical "Košna" conglomerates (**Fig. 28**) are petromict conglomerates consisted mainly of limestone clasts, but also of sandstones and quartz. Matrix is usually psamitic, but it can be also carbonate. Petromict nature of these conglomerates indicates on diverse origin rocks, which were eroded in base (Sokač et al., 1976).

Fig. 28. Košna spring – "Košna" conglomerates from Middle Permian.

Stop 4: *(Brušane -Kalvarija and Paripov jarak)*

Kalvarija -- Permian shales and limestone succession

This location has a local toponym Kalvarija or Velnačka glavica, and it is located in Brušane village. Here are outcrops of subvertical layers of black limestone, which are part of big succession of carbonate rocks of Middle to Upper Permian, developed in three parallel zones of limestones divided with dolomites (Sokač et al., 1976). It has been found in this limestones 35 species of microfissils, which can be used for stratigraphic determination: *Gymnocodium bellerophontis*, *Mizzia velebitana*, *Velebitella triplicate*, *Salopekiella velebitana*, *Gymnocodium bellerophontis*, *Eoverkebeena salopeki* and others (Sokač et al., 1967; Fio et al, 2013). All three zones of limestones are characterized with bituminous black, mostly bioclastic limestones interlayered with thin layers of shaly limestones (**Fig. 29**).

These limestone sequences often contain pyrite. First zone of limestones, or Lower Limestone Zone (Fio et al, 2013) mostly contain gastropods, brachiopods, crinoids and nautilitides macrofossils, and according to fossil content, it is determined as Mid Permian. The Second zone or Middle Limestone zone, has a very rich fossil content, commonly represented by platform algal "medows" with sporadic patch-reefs (or Lower Limestone Zone (Fio et al, 2013), gastropods, ostracods and hydrozoa.

This zone belongs to Upper Permian, just like the third zone or Upper Limestone Zone, which has the similar fossil assemblage (Fio et al, 2013).

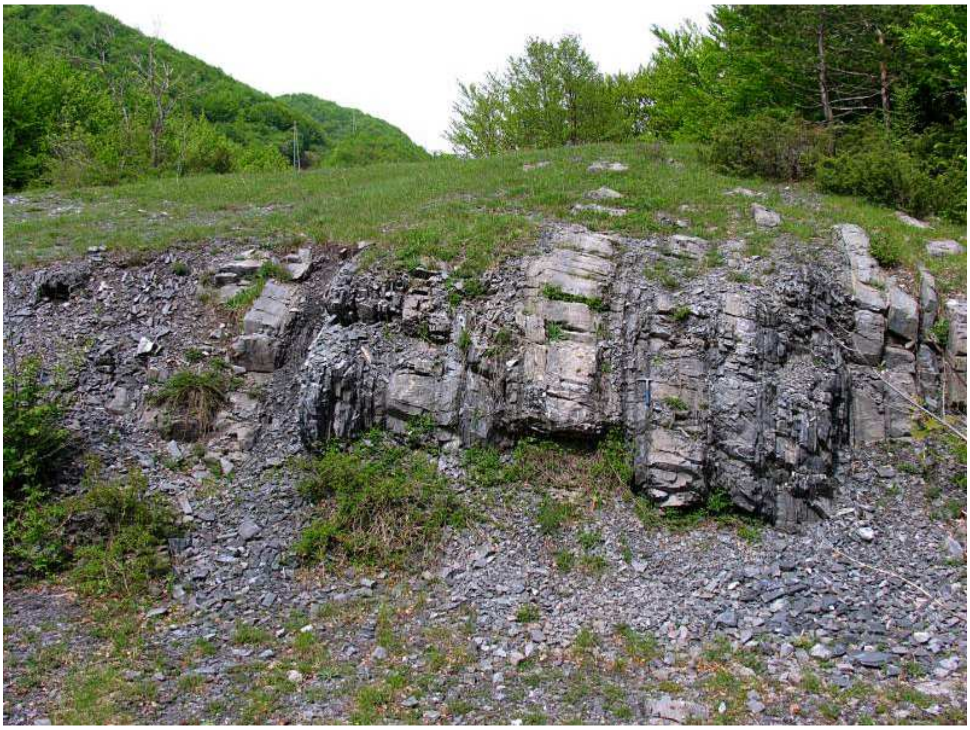

Fig. 29. Karvarija location with Limestones from Middle to Upper Permian carbonate succession.

Paripov jarak -- Permian limestone and dolomite succession

Middle to Late Permian platform carbonates deposits are well exposed along Gospić-Karlobag road, in vicinity to Brušane. Along with described limestones on Kalvarija, middle and upper Permian is primarily built from dolomites, which represent unique complex of deposits from Middle Permian clastic rocks to Triassic sediments. These dolomites are full of fossil content, with numerous remains of corals, brachiopods, shells and specially microfossils which are described in study of Kochansky-Devidé (1965). In dark dolomites can be found *Mizzia Velebitana, Mizzia yabei, Mizia cornuta, Velebitella tripicita, Salopekiella valabitana, Vermiporella sp., Gymnocodium bellerephontis, Eoverkeebina cf. salopeki, Eoverkeebina paklencienssis, Shaperulina cf. croatica.*

Just like limestones, dolomites are developed in three zones, of which the first one ("Mizzia" dolomites) are without terrigenous components, with low $CaCO_3$ content. Macroscopically, it is easy to notice white dots, which represent recrystallized remains of organic meter. Genetically they are defined originally as biocalcarenites transformed in to dolomites during early diagenesis. "Mizzia" dolomites (**Fig. 30**) gradually transition into second zone of limestones, which than change to second zone of dolomites ("Neoschwagreina" dolomites). These dolomites are pale grey in colour with rare interlayers of dark dolomites. Genetically they are the same as the "Mizzia" dolomites, but poorer in fossil content. They are also more recrystallized then first zone, but in their upper part, they are again much darker with much better preserved fossil content. Stratigraphically, above them is the third zone of limestones, which again changes in to final zone of Permian dolomites – "Transitional" dolomites. They are well-bedded with pale color. They have crypto to microcrystal structure, and poorly represented with fossils. High degree of dolomitization, fine stratification, microcrystal structure along with absence of point to primary origin of these dolomites (Sokač et al., 1976).

Fig. 30. Paripov jarak location on the Gospić – Karlobag road with Upper Permian carbonates.

Stop 5: *(Entrance of Baške Oštarije)*

Permian-Trassic Boundary - PTB

Boundary between Permian and Triassic is visible along the road Gospić – Karlobag, at the eastern entrance of the Baške Oštarije village (**Fig. 31**). The youngest Permian rocks are "Transitional" Dolomites (**Fig. 31**), which comprises well-bedded, early- to late-diagenetic dolomites, usually containing skeletal voids and fenestral fabrics. Lower part of this unit comprises in places a relatively thin succession of reddish or rarely grey-greenish clastites (which may represent temporal equivalent of Gröden sandstones in the Alps). Commonly, dolomites are laminated with nodular bedding surfaces and containing variable amount of biodetritus. Overlying the "Transitional" Dolomites is the "Sandy" Dolomite, relatively rich in terrigenous material, commonly lacking in fossils in its lower part, characterized by dolomites alternating with mica-sanstones and siltites, as well as rare thin layers composed of ferrigenous ooids.

The litostratigraphic boundary between those two units, characterized by depositional break caused by regional emergence, was previously considered as the PTB. The results of the detailed geochemical study (Fio et al., 2010) showed that lithologic boundary doesn't represent actual PTB. Instead is defined chemostratigraphic boundary, several meters above lithologic boundary, based on development of water column anoxia-euxinia event (Fio et al., 2010).

Fig. 31. Gospić – Karlobag road in the vicinty of eastern entrance of Baške Oštarije where Permian – Triassic boundary is exposed.

Stop 6: *(Prpići-Baške Oštarije)*

Diplopora limestone—*Anisian±Ladinian (c.247.2-237.0 Ma)*

Diplopora limestone i.e., ***"Klimenta"*** limestones outcrops in the vicinity of settlement Prpići in the area of town Baške Oštarije. These limestones crops out in the nearby creek as a massive, poory layered limestones (**Fig. 32**). These limestones are very similar, and can be distinguished only on the basis of fossil content (Grgasović, 2007). Being rich in fossil dasycladalean algae *Diplopora annulata and Kantia dolomitica* (thalluses are visible as small rings, elipses, or elongated algae exteriors; **Figs. 33** and **34**) this Middle Triassic limestones are light grey, resembling recrystalized sparitic limestone of various textural types (mudstone, wackstone, fenestral mudstone, peloid-intraclastic packstone-grainstone and oncoidal floatstone) that are characterized by stylolitic structures (Grgasović, 2007). The contact with hangingwall Upper Triassic dolomite succession is often erosional, being marked with terrigenous red clastics. Diplopora limestone is often irregulary karstifed due to to Ladinian-Carnian emergence which formed significant paleorelief that in some areas promoted depostion of bauxite strata with max. 40-70 m of thickness (Tišljar et al., 2007). The total thickness of Diplopora limestone succession in area of Mt. Velebit reach approx. 500 m.

Fig.32. Outcrop of *Diplopora limestone* in the vicinity of settlement Prpići.

Fig. 33. Detail of the *Diplopora limestone* with makroscopically visible remnants of *Diplopora annulata* (road Sv. Rok-Mali Alan-Obrovac- *c. 45 km SW)*.

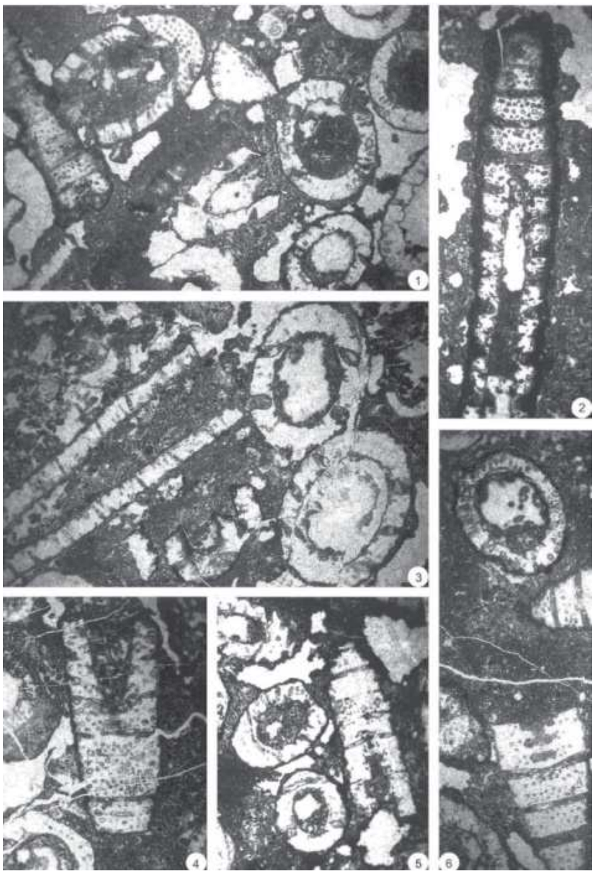

Fig. 34. Microscopic section of microfacies of *Diplopora annulata* SCHAFHÄUTL and Kantia dolomitica PIA. Sv. Rok–Mali Alan Road, Ladinian. Each ring (annulum) bears two whorls of trichophorous branches (after Sokač, 2007)

Stop 7: *(Prpići-Baške Oštarije)*

Upper Triassic clastic series—*Carnian-Norian (c.237.0 - 208.5 Ma)*

Upper Triassic clastic series crops out instantenously above Diplopora limestones in the nearby creek in the settlement Prpići in the area of town Baške Oštarije (**Figs. 35**). In the Mt. Velebit area these terrigenous clastic succession, i.e. red clastics, claystones, conglomerate and even hematite bauxite are related to longlasting continental emersion phase and formation of paleorelief in Middle/Upper Triassic time (Ladinian-Carnian emergence for approx. 21 Ma). Accordingly, in some places this emergence resulted in either direct contact between Diplopora limestone and Upper Triassic dolomites or enabled deposition of significant series of clastic material, i.e., red clastics, conglomerates in paleodepressions by periodic flods of fresh water and marine ingressions (**Figs. 36** and **37**). (c. ≤ 100 m. thick succession; see Tišljar et al., 2007 for details). At certain locations, similar to obseved one, beside red clastic often could be found greenish tufitic slitsones and sandstones, carbonate breccias and intertidal to subtidal marine coastal deposits i.e., Upper Norian carbonates (dolomitized limestones, fenestral and stromatolitic dolomites, late-diagenetic dolomites), (**Fig. 38**; see Tišljar et al., 2007 for details). The tufitic component was direct result of volcanic activity that was recognized at that time but in areas more to the north, in the area of Pazarište, Fužinski Benkovac and Senjska Draga.

Fig. 25. Outcrop of Upper Triassic red clastic series above *Diplopora limestone* in the vicinity of settlement Prpići.

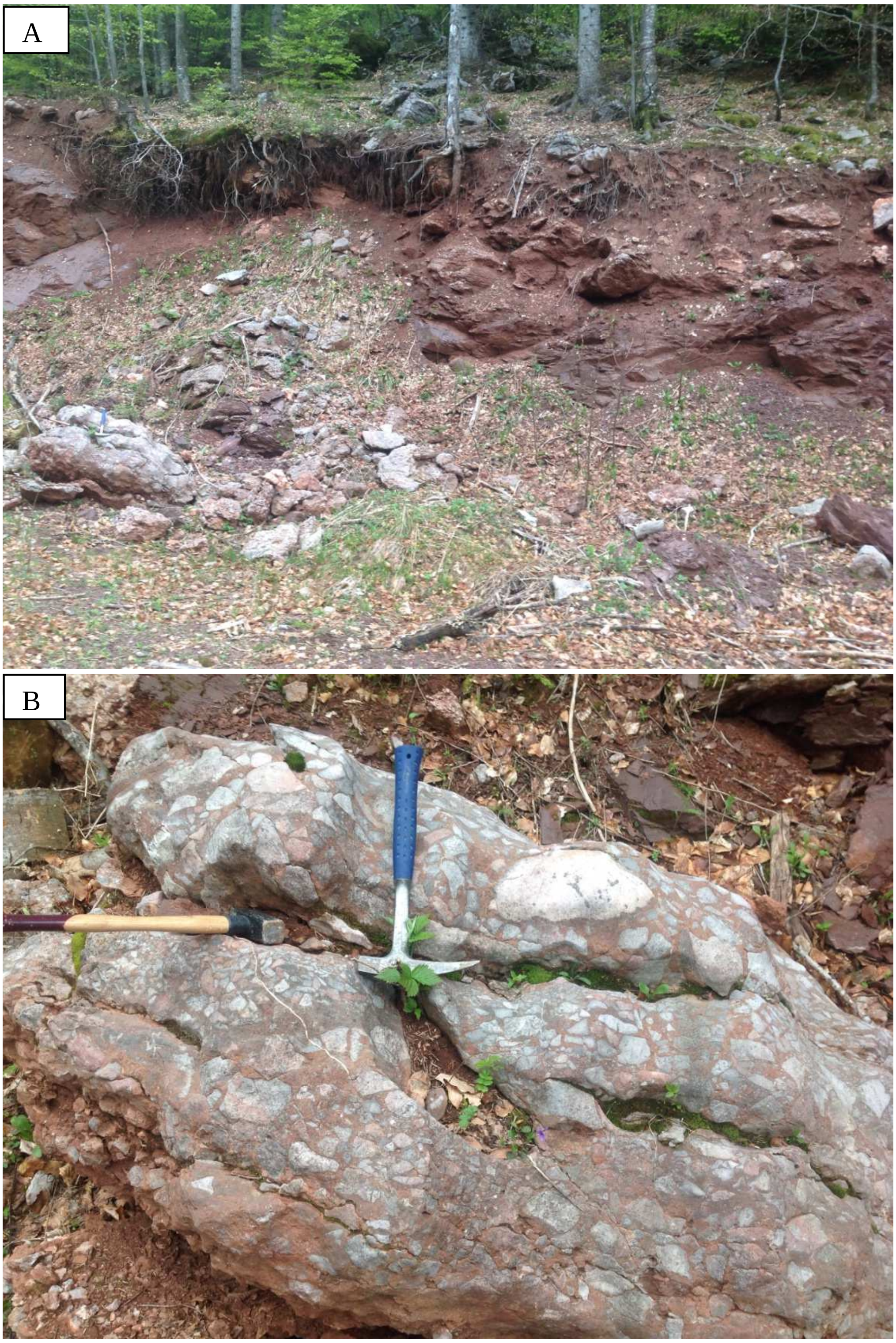

Fig. 36. A) Outcrop of red clastics and conglomerates c. 6 km to the NE (locality of Jadovno). B) Outcrop conglomerate detail.

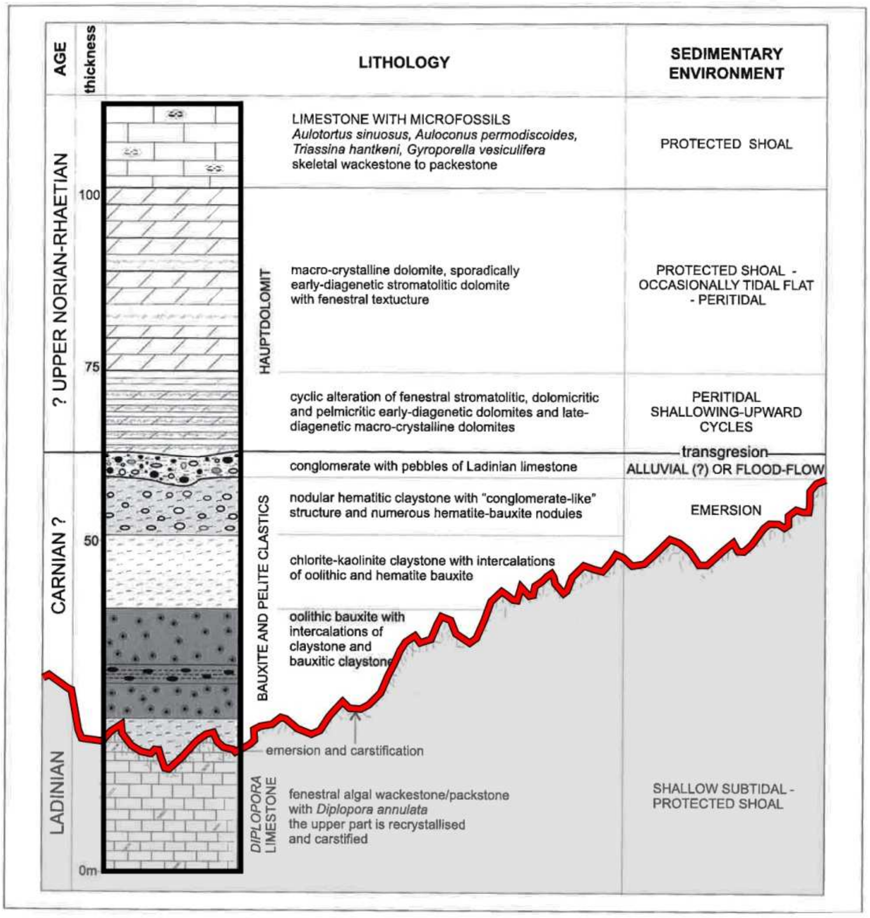

Fig. 37. Shematic geological column of Vrance locality (c. 60 km to the SE, near Gračac; see Tišljar et al., 2007 for details).

Fig. 38. Outcrop of Upper Norian? carbonates just above Upper Triassic red clastic series and *Diplopora limestone* in the vicinity of settlement Prpići.

Stop 8: *(Prpići-Baške Oštarije)*

Upper Triassic Hauptdolomite formation—*Norian-Rhaetian (c.208.5-201.3 Ma)*

- c. 500 m NE and NW in relation to settlement Prpići

After Middle/Upper Triassic emersion phase, gradual ingression of the Late Norian sea resulted in deposition of dolomite sequence of "Main dolomite" or Hauptdolomite/Dolomia principale (Velić, 2007a). This sequence of distinguishable light and dark grey layered early-diagenetic and late-diagenetic dolomites represent peritidal alternation that is in some places c. 250 m thick. Early-diagenetic dolomites are characterized by stromatolitic texture, whereas late-diagenetic dolomites are characterized by recrystallized structure.

Within the Hauptolomite formation there are also sporadic occurences of interlayered bioclastic calcarenitic strata with peudoolitic-oolitic texture. In the Mt. Velebit area, Haupdolomite formation age is primary dated by preseved fragments of Norian carbonate algae *Gyroporella vesiculifera* and secondly by superposed position in relation to early Jurassic limestone and dolomite succession (Sokač et al., 1976). At the observed location, early and late-diagenetic dolomites of Hauptolomite formation are found in the hangingwall of the Upper Triassic clastic succession and Upper Norian carbonates as numerous fragments covering hillslopes (**Fig. 39**), whereas outcrops are relatively small and scarce being dominantly composed of early-diagenetic dolomite succession (**Figs. 40**).

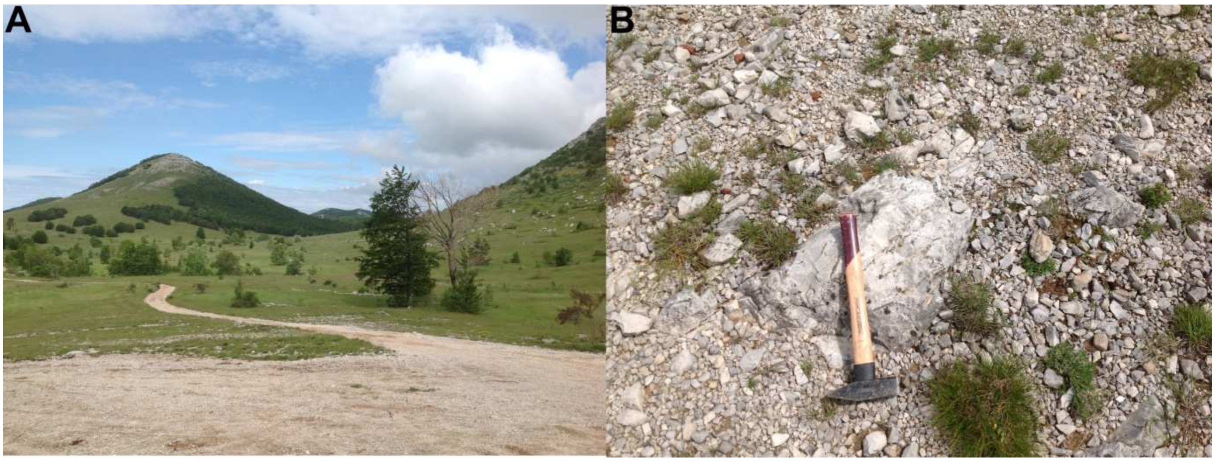

Fig. 39. A.Landscape in Hauptdolomite formation in the vicinity of settlement of Prpići-Baške Oštarije. B. Fragments of late-diagenetic dolomites covering landscape formed within Hauptolomite formation.

Fig. 40. Outcrop detail of early-diagenetic dolomites within Hauptdolomite formation.

Stop 9: *(Kubus pass-Baške Oštarije)*

Lower Jurassic limestone and dolomite succession—*Hettangian-Sinemurian (c. 201.3-190.8 Ma)*

At the Stop 9, in the vicinity of town Baške Oštarije, the Hettangian and Sinemurian limestone and dolomite succession is the best exposed on several surrounding peaks e.g., Basača (1089m), Kubus pass (968m) and Badanj (1164m). (**Figs. 41** and **42**). These Lower Jurassic carbonate succession is characterized by well-bedded, grey limestones that resembles alternation of skeletal-intraclastic grainstone and mudstones (deposited in shallow subtidal with periodic emersions into the vadose zone) and microcrystalline late-diagenetic dolomites and stromatolitic dolomites interchanged with well layered micrites, oncoid and peloid wackstones,oolitic grainstones and rare intraformational breccia. Going towards younger parts of this succession dolomitic strata disapear. At our stop, we can find well-bedded and steepy inclined alternation of mudstones, fossiliferous wackstones, peloidal grainstones and oncoidal-bioclastic, gastropod rich grainstones that are interchanged with late-diagenetic dolomites (**Fig. 42**). Limestones are rich in algal remnants and gastropods. Fossils (**Fig. 43**) are primary dominated by algae *Paleodasycladus* (e.g, *P. meditereaneus, P. mediterraneous var. heraki, P. mediterraneous var. illyricus, P. mediterraneous var. elongatus, , P. alanensis, P. benecki,* etc.) and foraminiferal assamblage (e.g., *Lituosepta* *recoarensis, Orbitopsella primaeva, Orbitopsella praecoursor*, etc.) The depositional enviroments were peritidal shallowing-upwards cycles-intertidal banks (see Sokač, 2007 for details). The total thickness of Lower Jurassic limestone and dolomite succession reach c. 210 m (Sokač, 2007).

Fig. 41. Outcrop of Lower Jurassic limestone and dolomite succession at theBadanj peak (1164 m).

Fig. 42. Outcrop of Lower Jurassic limestone and dolomite succession at the Kubus pass(1044 m). Strata are characterized by steeply inclined bedding plains, and strata with c. 30-100 cm thickness.

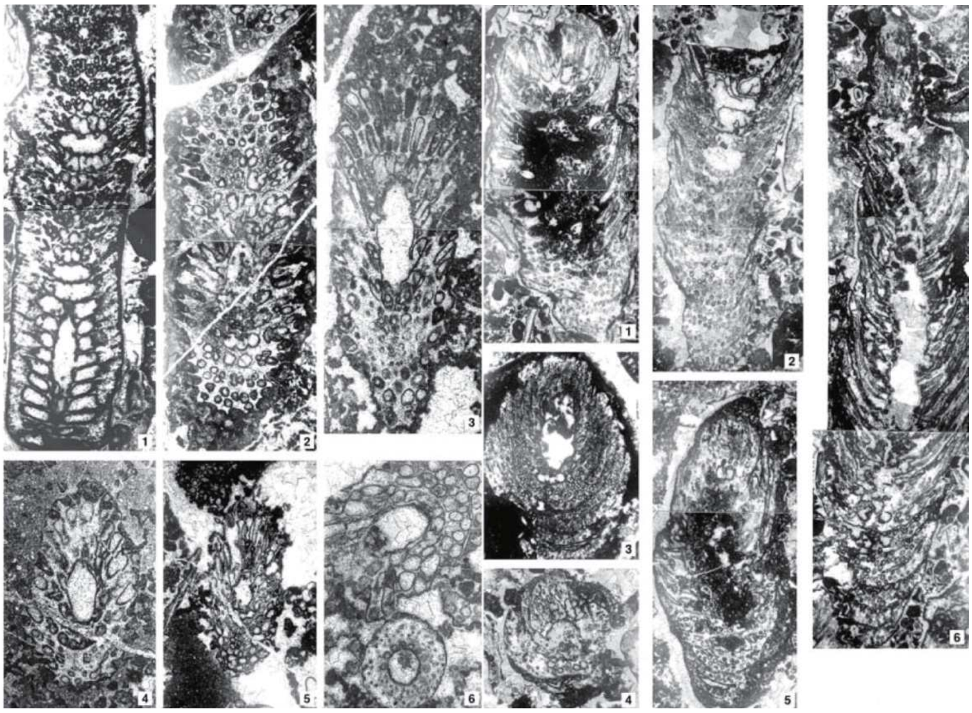

Fig. 43. Microscopic section of microfacies of *Palaeodasycladus mediterraneus* var. *heraki, Palaeodasycladus mediterraneus* var. mediterraneus, *Palaeodasycladus mediterraneus* var. *gracilis.*. Bundles of secondary branches are clearly visible. Sample localities and ages--VT: Mali Alan Pass, central Mt. Velebit, Lower Liassic; JD: Jadièevac, central Mt. Velebit, Lower Liassic; TG: Mt. Trnovski Gozd, western Slovenia, Middle Liassic (after Sokač, 2001).

Stop 10: *(Kubus pass-Baške Oštarije)*

Lower Jurassic Lithiotid limestone unit—*Plinsbachian-Toarcian (c. 190.8-174.1 Ma)*

c. 300 m W in relation to Kubus pass

Due to continous subsidence of the AdCP in the Lower Jurassic, Hettangian-Sinemurian limestone and dolomite succession in the investigated area were covered by mud-supported limestones (**Fig. 44**). Deposited in the deeper subtidal and lagoonal enviroments under reducing conditions, fossiliferous, skeletal-bioclastic mudstones, wackstones, floatstones and rudstones alternating with mudstones, wackstones, peloidal packstones were formed (Velić, 2007). This 215 m thick limestone succession (beds are between 40 -60 cm thick) in the topmost section is characterized by gravitiational structures, e.g., slump fold structures, formed by submarine gravitational slides. Lithiotides shells (**Fig. 45**) are transported at a relative small distances, often current-oriented, resembling 2 m thick cocina beds (**Fig. 45**). Lithiotides shells could be found either resedimented or in primary positon. Beside macroscopic fossils of Lithiotides, Brachiopodes and Gastropods (in the uppermost section), in this limestone unit many microfossils could be found. Calcareous algae and bentic foraminifera *Orbitopsella primaeva and Orbitopsella praecoursor* prevail (see **Fig. 46;** Velić , 2007b, c).

Fig. 44. Middle Lower Jurassic Lithiotides limestone unit steeply inclined towards SW *(c. 200 m W in relation to Kubus pass).*

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Fig. 45. Middle Lower Jurassic Lithiotides limestone detail with Lithiotis shells.

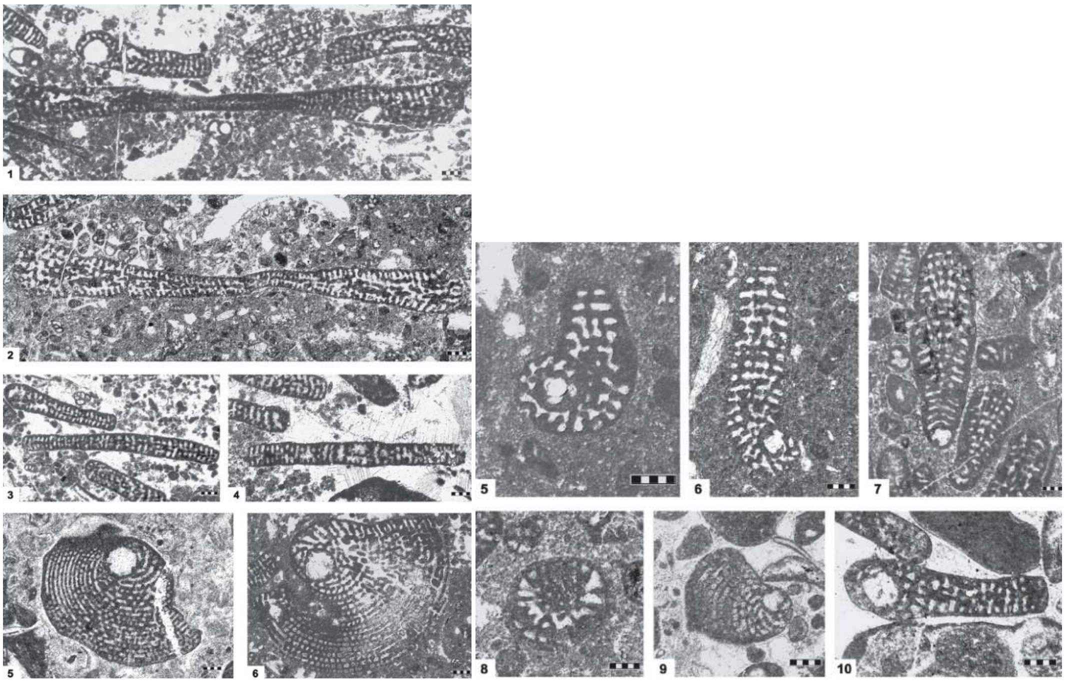

Fig. 46. Microscopic section of 1–4 Orbitopsella primaeva (HENSON), Late Sinemurian–Early Pliensbachian; 1 – megalosphaeric and microsphaerc forms, 2–4 – microsphaeric forms; 1, 3–4: North Velebit Mt., 2: Central Velebit Mt., Croatia. 5–6 Orbitopsella praecursor (GÜMBEL), Pliensbachian; megalosphaeric forms, 5: Central Velebit Mt., 6: Plitvice, Croatia. 5–8 Lituosepta recoarensis CATI, Late Sinemurian–Early Pliensbachian; 5–6: Central Velebit Mt., 7–8: Gornje Jelenje, Croatia. 9–10 Orbitopsella primaeva (HENSON), Late Sinemurian–Early Pliensbachian; megalosphaeric forms, 9–10:South Velebit Mt., 11: North Velebit Mt. Scale bars – 0.2 mm (after Velić, 2007).

Stop 11: *(Kubus pass-Baške Oštarije)*

Lower Jurassic Fleckenkalk, "Spotty" limestone unit—*Toarcian (c. 182.7-174.1 Ma)*

c. 2 km from Kubus pass along the road towards town of Karlobag

At the Stop 11, along the road to town Karlobag, c. 2 km from Kubus pass, in the hangingwall of steeply inclined beds of Litiotides limestone unit, we can observe Fleckenkak or "Spotty" limestone unit (**Figs. 47**). With total thickness of c. 120 m, this thin bedded strata (10-60 cm strata) represent intensively bioturbated mudstone/wackstones (**Fig. 48**). Spotty pattern (german "Fleckenkalk") is result of heavy bioturbation of dark, organic material rich mudstones that were deposited in the deeper subtidals and restricted lagoon settings under oxegen reduced conditions (Vlahović et al., 2005). These oxegen reduced conditions coincide with Toarcian oceanic anoxic event (OAE) tha slowed down deposition and was associated to the tectonically susided parts of AdCP platform (Vlahoviće et al., 2005; Velić, 2007c). Beside numerous feeding-associated textures, Spotty limestone also contain biclasts and ooids. Spotty Limestone unit could be recognized as a landscape and landform forming factor due to its erosion-prone characteristics which promote low and gentle relief in the Karstic terrains, considerably different than relief forms in surrounding younger and older rocks.

Fig. 47. Fleckenkalk, "Spotty" limestone unit at Stop 11 (c. 2 km from Kubus pass, along the road towards the Karlobag).

Fig. 48. Fleckenkalk, "Spotty" limestone unit in detail with fossil bioturbations.

Stop 12: *(Žuti Vrh-Kiza peak-1274m)*

Carbonate polymictic breccia unit (Velebit/ Jelar breccia) —*Eocene-Oligocene? (c. 56.0-23.03 Ma)*

At the Stop 12, after a short walk from Kubus pass to Kiza peak (1274 m), massive Eocene - Oligocene carbonate breccia units i.e., Velebit/Jelar breccia will be observed (**Fig. 49**). The Velebit/Jelar polymictic breccia is know non-bedded, clast-supported sedimentary structures to cover W and SW slopes of Mt. Velebit, c. 2 km wide and 100 km long area, as well as parts of hinterland associated to the Lika Region (**Fig. 24**). The origin of breccia is not completely understood but it is considered that is associated both to tectonic uplift and formation of Mt. Velebit as well as weathering processes associated to uplifted Mesozoic and Paleogene successions. Clast size within breccia complex is extremely variable, depending on a degree of tectonization and mechanical disintegration, angular to subangular, from several mm to several dm to even meter-sizes. Velebit breccia are in most cases in disconformable or tectonic contact with Upper Jurassic and Lower Cretaceous limestones, reaching the total thickness of c. 600 m (**Fig. 50;** in the vicinity of the Tulove Grede-Sv. Rok tunnel; see Vlahović et al., 2012 for details). Carbonate breccia are generally clast-supported, with either greyish or reddish matrix (**Fig. 51**). The age of Velebit/Jelar breccia is estimated in accordance to the source clasts that in vicinity of Baške Oštarije are dominated from Jurassic, Cretaceous to Eocene (e.g., Foraminiferal limestone unit) in age (see **Fig. 51**). In te SE part of Mt. Velebit large amounts of tectonically fragmented material were transported by alluvial systems that yielded contemporus thick sequences of Promina conglomerates (Velić et al., 2007).

Fig. 49. Massive carbonate polimiknic breccia in the footwall of Kiza peak (1274m).

Fig. 50. An overview of Tulove grede, part of Mt. Velebit peaks composed of c. 600 m of Velebit breccia unit (*in the SW part of Mt. Velebit, in vicinity of Sv. Rok tunnel*).

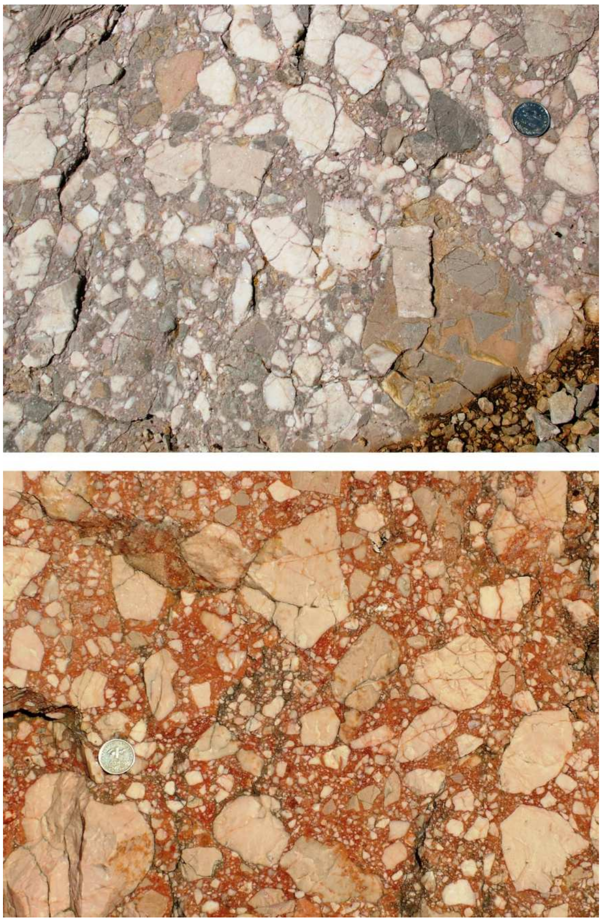

Fig. 51. Velebit/Jelar breccia unit. Examples with greyish and redish matrix. These massive breccia is consisted of clasts of Mesozoic and Paleogene sedimentary rocks.

EXCURSION—E3

Excursion leader: Asst. Prof. Uroš Barudžija, PhD

Istria peninsula

An introduction to the geology of Istria

Introduction

The introduction to the geology of Istria presented here is based and partly cited on the paper "A Review of the Geology of Istria" (Velić et al., 1995a) from the Excursion Guidebook of the First Croatian Geological Congress-Opatija1995 (edited by Vlahović & Velić) and the papers presented in the Field Trip Guidebook of 22nd IAS Meeting of Sedimentology-Opatija2003 (edited by Vlahović & Tišljar).

Although intense post-sedimentary, Tertiary tectonics have significantly affected the entire area of the former Adriatic Carbonate Platform (Vlahović et al., 2005), resulting in the very complex tectonic pattern of the area, there are localities with quite well preserved stratigraphic records enabling recognition of important events in the geological history of the Adriatic Carbonate Platform. One of them is Istria, a peninsula located on the NW part of the Croatian coast, with an area of c. 3000 km^2. From the geological point of view, Istria can be divided into three regions:

1) the Jurassic–Cretaceous–Eocene carbonate plain of S and W Istria,
2) the Cretaceous–Eocene carbonate–clastic zone, characterised by overthrust structures in E and NE Istria (from Plomin and Učka Mt. to Ćićarija Mt.), and
3) the Eocene flysch basin in central Istria.

The geological peculiarities of these regions had been noticed historically by the inhabitants of Istria, who coined specific names for them:

Red Istria – the southern and western Istrian plain named after the *terra rossa* covering a large part of the younger Mesozoic and Eocene carbonates;
White Istria – in eastern and north-eastern Istria, characterised by karstified outcrops of "white" Cretaceous–Eocene limestones; and
Gray or Green Istria – in central Istria, characterised by Eocene flysch.

Stratigraphic succession of Istria

Compiled and partly cited after*: Velić, I., Tišljar, J., Vlahović, I., Matičec, D. and Bergant, S. (2003):Evolution of the Istrian part of the Adriatic Carbonate Platform from the Middle Jurassic to the Santonian and Formation of the Flysch Basin During the Eocene: Main Events and Regional Comparison*

The Istrian succession consists predominantly of carbonate rocks ranging in age from Late Middle Jurassic to Eocene, with subordinate Eocene siliciclastic rocks, flysch and calcareous breccia, and Quaternary terra rossa and loess. The Istrian Late Middle Jurassic to

Eocene succession can be divided into four sedimentary units or large-scale sequences of carbonate deposits bounded by important discontinuities (emersion surfaces), covered by Quaternary deposits. The following large-scale sequences have been distinguished (**Fig. 52**):

1) Bathonian–lowermost Kimmeridgian;
2) Upper Tithonian–Lower/Upper Aptian;
3) Upper Albian–Upper Santonian;
4) Eocene;
5) Quaternary.

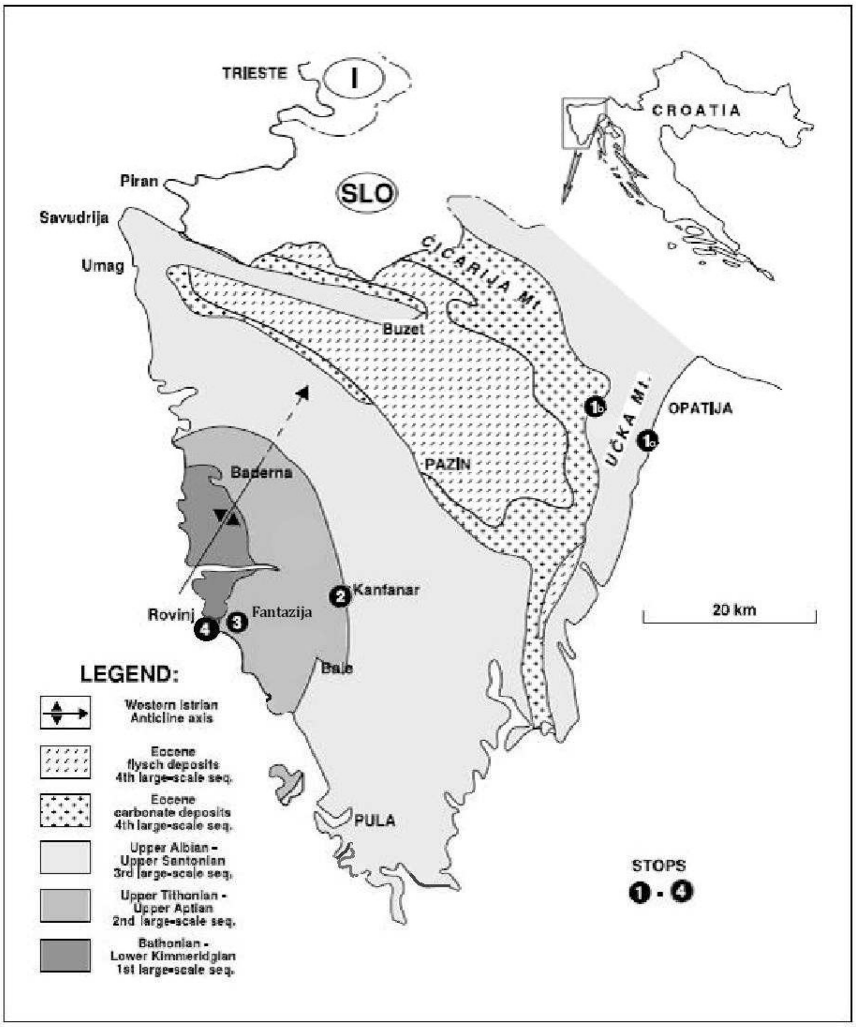

Fig. 52. Map showing the schematic distribution of large-scale sequences in Istria and the location of the Western Istrian anticline (partly modified after Velić et al., 1995a), with locations of the excursion stops. Deposits of all large-scale sequences of Istrian carbonates and flysch are for the most part irregularly covered by relatively thin Quaternary deposits (5th large-scale sequence).

1) Bathonian–lowermost Kimmeridgian large-scale sequence

This large-scale sequence is mainly characterised by a shallowing-, and coarsening-upward trend, which in the uppermost part is expressed by the appearance of a regressive breccia (the Rovinj breccia – Velić & Tišljar, 1988), and a final emergence surface with bauxite deposits. It is predominantly represented by different types of shallow-water limestones, which crop out in western Istria.

In the Bathonian and Callovian, restricted shallow subtidal and lagoonal environments prevailed, characterised by deposits of medium- to thick-bedded mudstones and fossiliferous wackestones (the ***Monsena Unit*** after Velić & Tišljar, 1988). In the Bathonian deposits, elements of synsedimentary tectonics have been documented. Similar depositional environments also predominated during the oldest Oxfordian, resulting in the deposition of peloidal packstones and wackestones (the ***Lim Unit***, after Velić & Tišljar, 1988). During the Middle and Late Oxfordian, sand bars composed of ooids and bioclasts were formed in high-energy shallows and the marginal parts of lagoons, which gradually prograded (tidal bars – Tišljar & Velić, 1987; the ***Muča Unit***, after Velić & Tišljar, 1988). The shallowing-upward tendency continued to the end of the Oxfordian, and during the earliest Kimmeridgian resulted in the formation of the regressive ***Rovinj (Vrsar) breccias***, representing the end of this large-scale sequence. They are composed of clasts from the immediate footwall (*Lim and Muča limestones*). Complete emersion and karstification followed, which is shown by the formation of an intense relief associated with an accumulation of source-material for the formation of clayey bauxites. In some places important quantities of bauxite have been formed.

2) Upper Tithonian–Lower/Upper Aptian large-scale sequence

This large-scale sequence is very complex, especially with regard to its facies heterogeneity and great thickness. From the lithological point of view, different types of peritidal deposits predominate, especially pelletal limestones and LLH-stromatolites, with subordinate emersion breccia with clayey matrix (Tithonian, Hauterivian, Barremian), early- and late-diagenetic dolomites (Berriasian), and grainstones (bioclastic sand bar deposits in the Upper Valanginian and Upper Barremian). Deposits of this large-scale sequence crop out from Poreč, in the form of an arc (**Fig. 52**), near Kanfanar and Bale, to the coast from Rovinj to the island of Veli Brijun.

The large-scale sequence started in the younger Tithonian with an oscillating transgression, i.e. shallowing-upward cycles (dm–m scale) deposited in subtidal, intertidal and supratidal environments. These limestones, used as an architectural-building stone called *“Pietra d’Istria”* or *“Kirmenjak”*, are composed of black-pebble breccia/conglomerates, mudstones and fenestral mudstones with desiccation cracks, including the oldest dinosaur tracks in Istria. The uppermost part of the Upper Tithonian limestones is more or less late-diagenetically dolomitised.

Relative shallowing during the Berriasian and older Valanginian resulted in the deposition of limestones in subtidal and intertidal environments, which were later almost completely late-diagenetically dolomitised, though with early-diagenetic dolomites forming in supratidal environments. This alternation of late and early-diagenetic dolomites is known by the name of *“Fantazija dolomites”* (Velić & Tišljar, 1988) – **STOP 3** on **Fig. 52**.

In the younger Valanginian, mainly subtidal parasequences prevailed, sporadically characterised by a coarsening-upward tendency. A similar situation, but with numerous short-lasting emersions, continued in the Hauterivian and a major part of the Barremian, when shallowing-upward cycles were characterised by frequent LLH-stromatolites, numerous emersion surfaces and peritidal breccia. Footprints of dinosaurs have been found in such Barremian rocks on the island of Veli Brijuni, as well as bones on the sea floor near the western coast of Istria.

By the end of the Barremian, bioclastic carbonate sand bars characterised by cross-bedding were being deposited in shallow subtidal-intertidal environments. The transition to the Aptian was characterised by a change in the depositional system, which, throughout the whole of Istria, involved a sudden and relatively important relative deepening, into restricted lower subtidal and/or lagoonal environments with sporadic pelagic influences. Therefore, the Lower Aptian is characterised by thick-bedded to massive floatstones with oncolites, Bacinella and requieniids (Toucasia sp.), which are well-known as the architectural-building stone *"Istarski žuti"* (*"Istrian Yellow"* – named after its yellowish colour) – **STOP 2 (Fig. 52)**.

Upper Aptian deposits in Istria experienced relatively rapid shallowing, resulting in complete emersion. This regional emersion phase was the result of a relative fall in sea-level caused by the interaction of eustatic changes and synsedimentary tectonics on the Istrian part of the Adriatic Carbonate Platform. These movements resulted in the variable duration of shallow-water environments on different parts of the platform, as well as in the different intensity of erosion of the Aptian and Barremian deposits. Finally, the end of the large-scale sequence was marked by deposition of emersion breccia and conglomerates, with clay and black swamp deposits, which are well exposed in a complete zone in western Istria.

3) Upper Albian-Upper Santonian large-scale sequence

This large-scale sequence is very thick (up to several 100s meters) with a very variable facies succession. Therefore, in this review we will discuss only the basic lithological characteristics of some chronostratigraphic units, especially those covered by our excursions.

After extensive emersion during the late Aptian and early Albian, at first a gradual, and later a complete ingression occurred during the middle of the Albian, i.e. it was accomplished by the beginning of the late Albian. Thus, the shallow-water platform carbonate system was re-established over the whole of the Adriatic Carbonate Platform that today belongs to Istria. However, several larger sedimentary units can be separated, each characterised by relatively similar sedimentary conditions and environments.

These are:

a) the peritidal and foreshore sedimentary system during the middle and late Albian;
b) differentiation of sedimentary systems during the Vraconian and Cenomanian;
c) the drowned platform system during the youngest Cenomanian and early Turonian;
d) the shallow-water sedimentary system during late Turonian, Coniacian and Santonian.

4) Eocene stratigraphic succession

The fourth large-scale sequence in Istria comprises a relatively thick succession of carbonate and siliciclastic rocks. Its greatest part crops out in the Pazin Basin and neighbouring areas.

The duration of the emersion phase between the Early to Late Cretaceous and Early Eocene is variable. Different members of the Eocene succession were transgressively deposited on different members of the Cretaceous basement, according to the differentiation caused by the Late Cretaceous tectonic phase (Matičec et al., 1996). Consequently, the succession of Eocene deposits is very variable in the lateral and vertical sense, especially concerning changed conditions in Palaeogene marine environments. In general, the deposits can be divided into the so-called Liburnian deposits, Foraminiferal Limestones, Transitional beds and Flysch deposits.

Liburnian deposits, locally present, were deposited in the lowest parts of the palaeorelief. They are characterised by an oscillating ingression, and are mostly represented by fresh-water to brackish, lagoonal deposits of the Early Eocene age.

Foraminiferal limestones in Istria can be divided into three or four lithostratigraphic types which are mostly in superpositional relationships. These are ***Miliolidae-, Alveolina-, Nummulites-*** and ***"Discocyclina"-limestones***, which specifically represent the uppermost part of the Nummulites-limestones. The foraminiferal limestones are mostly composed of whole and broken larger foraminiferal tests, with subordinate detritus of molluscs, ostracods, echinoderms, bryozoans and corallinacean algae, as well as glauconite grains and planktonic foraminifera in the uppermost part.

Transitional beds comprise a range between typical shallow marine and deep marine deposits. They consist of the so called "***Marls with crabs***" and ***"Globigerina Marls". "Marls with crabs"*** are well developed in the lower part of the Transitional beds as a thin (not more than 5m) zone of nodular-shaped deposits. They consist of clayey limestones, calcitic marls, composed of fine-grained carbonate and a siliciclastic matrix with glauconite. The fossil content is composed of planktonic foraminifera, bioclasts of benthic organisms and the often well preserved shells of crabs and echinoderms. The upper part of the **Transitional beds** consist of thick (few to several tens of m), massive ***"Globigerina Marls",*** sometimes with rare thin sandstone beds. Marls are rich with planktonic foraminifera and glauconite grains. They were deposited in significantly deeper environments (bathyal hemipelagic deposits) of Middle to Late Lutetian age (Middle Eocene).

Istrian flysch deposits (Istrian Eocene clastics) crop out in the Trieste–Pazin, Labin and Plomin basins, Mt. Učka (**STOP 1b; Fig. 52**), and partly on Mt. Ćićarija. They are generally characterized by an alternation of hemipelagic marls and gravity-flow deposits. The prevailing turbidite succession of hybrid carbonate-siliciclastic sandstones and marls is randomly intercalated with several thick carbonate beds of debrite origin, i. e. megabeds. The total thickness of Istrian flysch deposits is estimated as up to 350 m.

5) Quaternary deposits

Deposits of all the four previously mentioned large-scale sequences of Istrian carbonates and flysch are for the most part irregularly covered by relatively thin Quaternary deposits. The most important are loess and terra rossa, although there are also other types of palaeosols and soils.

Stop 1a: *(Učka)*

Basic tectonic characteristics of Istria

Compiled and partly cited after*: Vlahović, I., Tišljar, J., Velić, I., Matičec, D., Skelton, P.W., Korbar, T. and Fuček, L. (2003): Main Events Recorded in the Sedimentary Succession of the Adriatic Carbonate Platform from the Oxfordian to the Upper Santonian in Istria (Croatia)*

The tectonic pattern of the Croatian part of Istria is composed of three structural units. The Western Istrian Anticlinorium comprises the largest part of western and southern Istria, being composed of carbonate deposits of the Middle and Upper Jurassic in its oldest part, and surrounded by Cretaceous and Eocene carbonates. The second unit, the Pazin Flysch Basin, is composed of relatively thin Eocene limestones and thick flysch deposits, cropping out in the central and NW parts of the peninsula (**Stop 1b** in **Fig. 52**). The third unit is composed of stacked thrusted structures of Ćićarija Mt. in the northern part and of eastern Istria, as well as the Učka Nappe (**Stop 1a** in **Fig. 52**), which are composed of Upper Cretaceous and Eocene carbonates and Eocene flysch. The oldest record of tectonic activity in Istria has been found in the Upper Bathonian. These movements represent the oldest deformation in Istria, referred to as the D1 deformation. The effects of these movements were local emersion and a more intensified relief of the subtidal area. The movements were the consequence of mild compression and according to the orientation of gentle folds, they were accompanied by small faults, the greatest principal stress (σ1) being in the direction of 40–220°.

After a brief emersion, subtidal sedimentation was re-established, resulting in filling and levelling of the former relief. The continuity of sedimentation was not interrupted until the beginning of the Kimmeridgian when the area of Istria was influenced by a regional emersion that lasted through the major part of the Kimmeridgian and Early Tithonian. Emersion followed the relief formed mostly by steep conjugate faults. The latter brittle structures show striations perpendicular to the strike of the beds, and could have been formed only by extension (i.e. radial movements) oriented 30–210°. Since this orientation generally corresponds with the orientation of the stress during tectonic movements in the Upper Bathonian, it is possible to presume that these are only different phases of the same ***D1 deformation***.

Tectonic activity during the Cretaceous (***D2 deformation***) can be traced as periodic synsedimentary movements occurring throughout the period. Namely, the West Istrian anticline (anticlinorium) had already been formed in the Early Cretaceous (Matičec et al., 1996). All determined synsedimentary tectonic movements and the structures that they formed indicate the same orientation of stress. The orientation of these stresses and structures are identical with those of the West Istrian Anticlinorium. The hinge line of the west Istrian Anticlinorium dips north-eastward (towards 35°) and the greatest regional stress was acting along the direction 125–305°. Due to the persistent tectonic disturbance which consisted of compressional phases and phases of relaxation, it is possible that the hinge zone of the Istrian Anticlinorium existed as land until the end of the Cretaceous. By the end of the Cretaceous, almost the entire Adriatic Carbonate Platform, including the area of Istria, was affected by regional emersion of very variable duration. Emersion was the consequence of the final Cretaceous compression. The orientations of structures, obtained by the structural analysis of the dips of marker bed horizons indicate the same stress orientation as that previously recorded from synsedimentary tectonic movements during the Cretaceous. The Upper Cretaceous tectonic events initiated the disintegration of the former carbonate platform, and marked the end of typical, productive platform carbonate sedimentation, since renewed marine conditions in the Eocene had different characteristics.

The Eocene transgression was a consequence of a new, ***D3 deformation***. The intensity of these movements was witnessed by the formation of flysch basins, while their further increase resulted in a regional compression of the area. Hence D3 deformation became the decisive factor in the tectogenesis of the Dinarides. The result of this tectonic activity is obvious throughout the Adriatic coastline in the form of the so-called Dinaric strike of structures (approximately 315–135°). However, in Istria the beginning of subduction of the NE part of the Western Istrian Anticlinorium beneath the future structures of Ćićarija resulted in a differentiation of stress. The duration of the D3 deformation, i.e. the question of its upper boundary is not definitively denoted, because of the problem with stratigraphic determination in poorly developed terrestrial sediments. Anyway, these movements probably are partly Miocene in age.

Neotectonic deformation (D4) in the entire Dinarides is a consequence of the N–S oriented activity of the greatest regional stress. Neotectonic activity comprised either the formation of new, neotectonic structures, reactivation of inherited old brittle structures into the regional transcurrent faults, or rotation of already existing structures towards the new stress orientation.

Stop 1b: *(Učka- Road tunnel)*

Basic tectonic characteristics of Istria

Compiled and partly cited after: *Bergant, S., Tišljar, J. and Šparica, M. (2003): Eocene Carbonates and Flysch Deposits of the Pazin Basin.*

Istrian flysch deposits are characterized by the alternation of hemipelagical marls and gravity-flow deposits (**Fig. 53**). The predominant deposits are 5–40 cm thick beds of turbidites, the bases of which are missing, developed mostly as laminated and cross-rippled sandstone beds (Tb–e, Tc–e and Td–e Bouma sequences). Complete Ta–e Bouma sequences up to 100 cm thick are rare. Sandstones are of mixed carbonate–siliciclastic composition. According to the low ratio of arenite to marl thickness it could be concluded that the flysch deposits are of a distal character. Turbidites (**Fig. 53**) were deposited from low-density turbidity currents. The monotonous succession of marls and mixed carbonate–siliciclastic sandstones is intercalated with several thick carbonate beds composed of breccias, conglomerates, bioclastic arenites/siltites and marls. They show significant thicknesses of 0.5 to 5 m, sometimes over 10 m. These carbonate beds (megabeds) are interpreted as complex sequences of debris and turbidite origin and characterise the lower part of the basin fill. Some of them thin out and pinch out laterally, but the thicker ones are continuous over distances of more than 10 km. The base of these large beds is often flat, but sometimes shows shallow, wide erosional depressions.

There are two distinctive types of contact between the flysch and underlying deposits in the Istrian basin: a) continuous, and b) with erosional discordance between the flysch and carbonate ramp deposits.

Continuous deposition in the areas of Boljun, Kotli, Buzet, Šterna, etc., was characterised by gradual deepening from shallow-marine ***Foraminiferal Limestones*** to transitional beds with the first influence of a terrigenous contribution (**“*Marls with crabs*”).** Still further increases in the clay content led to the deposition of homogeneous hemipelagic marls (**“*Globigerina marls*”**). Flysch deposits begin with the occurences of alternating sandstone and marl beds.

On the southern border of the flysch area (e.g., in the vicinty of towns Motovun, Pićan), flysch deposits discordantly overlie different stratigraphic horizons of platform carbonates, i.e. Cenomanian limestones and Middle Eocene *Foraminiferal Limestones*.

The picturesque town of Hum („*The smallest town in the world*“!) is situated on the megabed, which is bedrock resistant to physical weathering unlike the distal flysch of central Istria. The thickness of the Hum megabeds is 7 m. There is an intense erosion surface between the lower bedding surface and the underlying marls. The lower part of the megabed of debrite origin, is composed of poorly sorted clasts from 10–30 cm up to several metres in diameter. Clasts of Cretaceous limestone prevail, while various types of Palaeogene limestones are rare. The matrix is comprised of fine-grained clasts and bioclasts of large foraminifera (orthophragminas, nummulites), corallinaceans and rare corals. Upwards, the megabeds gradually change character from debrites to carbonate turbidites, predominantly com-posed of sand with pebble-sized particles in their lower parts and a large amount of fine-grained bioclasts of large foraminifera, rare corallinaceans, and clasts of limestones, in their upper part. The Hum Megabeds are terminated by a thick pelite bed (Bouma Td–Te interval), containing clay and fine-grained particles of smaller foraminifera, planktonic foraminifera, bryozoans and echinoderms. This part of the megabeds is derived partly from turbidite currents and partly from hemipelagic sedimentation.

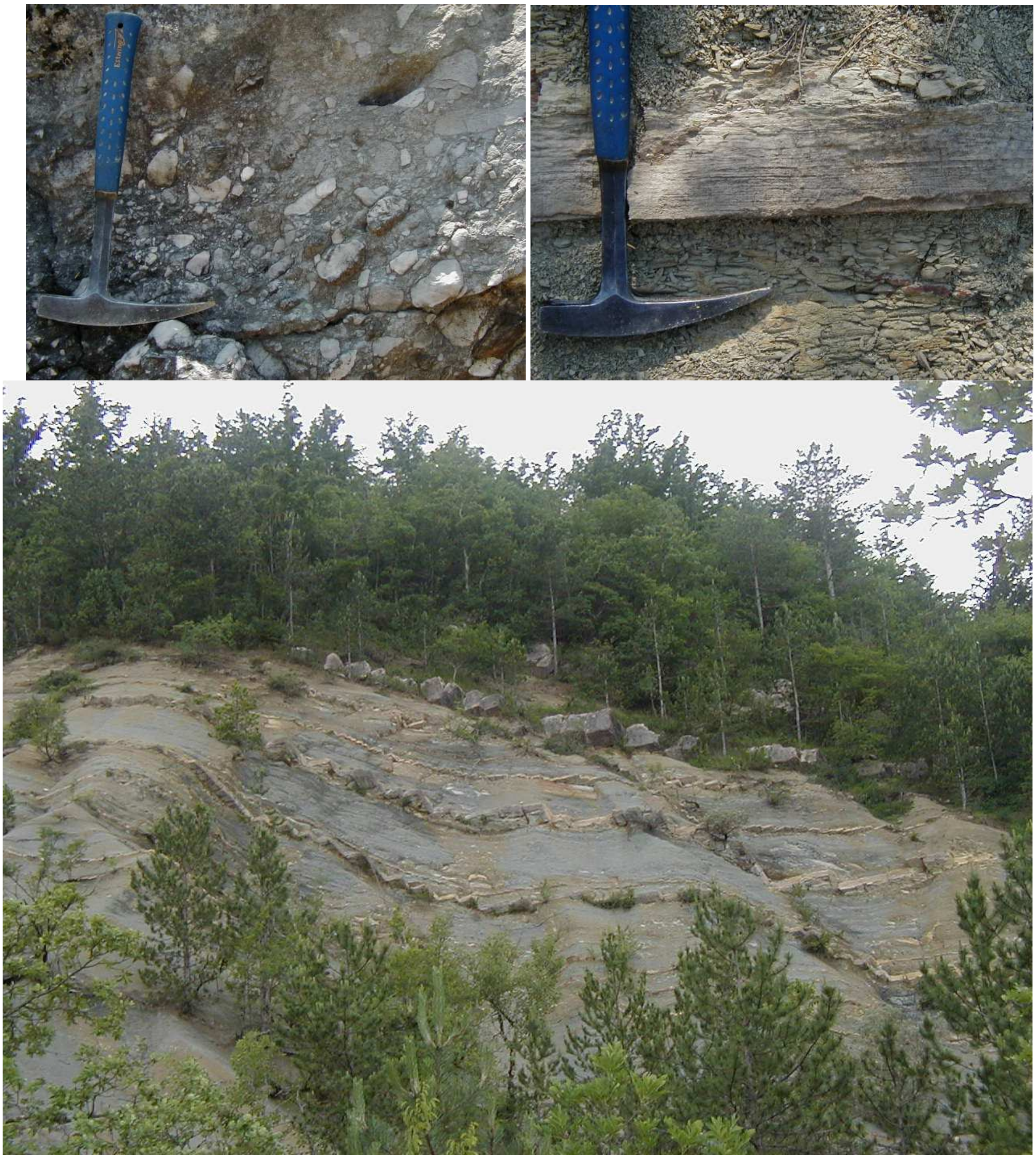

Fig. 53. Carbonate breccias and flysch deposits in the vicinity of settlement Čiritež.

Stop 2: *(Kanfanar quarry)*

Lower Aptian massive lagoonal oncolites/micrites and regional Late Aptian–Early Albian emersion in the Kanfanar quarry, central Istria

Compiled and partly cited after*: Vlahović, I., Tišljar, J., Velić, I., Matičec, D., Skelton, P.W., Korbar, T. and Fuček, L. (2003): Main Events Recorded in the Sedimentary Succession of the Adriatic Carbonate Platform from the Oxfordian to the Upper Santonian in Istria (Croatia)*

In the **Kanfanar quarry**, where the architectural-building stone known as ***„Istarski žuti“*** **(*„Istrian Yellow“*)** is exploited (**Fig. 54**), the boundary between the second and the third large-scale sequence of the Istrian succession is visible. Here one can find good outcrops of Lower Aptian oncolite limestones, plus only a 2–3 m thickness of Upper Aptian deposits, followed by a Late Aptian–Early Albian emersion surface and Late Albian deposits, representing the beginning of the third large-scale sequence.

The Lower Aptian oncolite limestones (**Fig. 54**) are underlain by carbonate deposits of the informal Dvigrad Formation (Vlahović, 1999), deposited during the Barremian, in peritidal environments of the inner part of the Adriatic Carbonate Platform. These are 68–78 m thick deposits, characterised by peritidal shallowing-upward cycles represented by alternations of mudstones, peloid wackestone/packstones to grainstones and LLH stromatolites. This unit is the culmination of a relative shallowing trend that is evident through the Lower Cretaceous succession, as indicated by common desiccation structures, dinosaur tracks, and large amounts of intertidal deposits. Shallowing-upward cycles in the lower and middle part of the Barremian are usually composed of subtidal pelletal or algal mudstones or wackestones, followed by intertidal, fenestral mudstones and LLH stromatolites or tidal breccia composed of reworked stromatolite fragments (Tišljar et al., 1983).

At the beginning of the Aptian, spacious low-energy shallows and lagoons were formed, where large amounts of fine carbonate detritus was deposited. The first 2–5 metres of the succession are commonly characterised by variable amounts of requieniid shells, mostly of *Toucasia* sp., and different benthic foraminifera, as well as numerous relatively large (1–8 cm) oncoids of *Bacinella irregularis* RADOIČIĆ. The Aptian limestones, referred to informally as the **Kanfanar Formation** (VLAHOVIĆ, 1999), can be divided into ***Lower Aptian massive oncolite limestones*** (**Sv. Petar Member** – known as the architectural-building stone ***„Istarski žuti“***, i.e. ***“Istrian Yellow”***, for its usual yellowish colour) and Uppermost Lower Aptian and Upper Aptian deposits of locally very variable thickness (the **Begovac Member**).

Massive Lower Aptian limestones (the facies of the architectural-building stone “Istrian yellow”) are very recognisable by their morphology in the field, and therefore represent a very good marker bed for geological mapping. They are composed of the cyclical alternation of two lithotypes: mudstones and oncolitic floatstones, which form thinner or thicker cycles. *Bacinella* oncoids (**Fig. 54**), which are typical components of the Lower Aptian limestones throughout the Dinarides, are always irregular in shape, and relatively large (mostly 5–80 mm), and are therefore sometimes referred to as "macroids". They have encrusting *Bacinella* skeletons in the central part, surrounded by a thinner or thicker oncoid envelope. Oncoids usually comprise up to 40% of the volume of the rocks, and in some parts, where they form oncoid crusts like hardgrounds with irregular surfaces and burrows, they are practically the only stratal constituents.

The Upper Aptian deposits are overlain by a 1–2 m thick bed of emersion breccio–conglomerates with clayey–marly matrix. The clasts are composed of fragments and pebbles of Aptian limestones and the matrix of emersion clays and/or marls and palaeosols. This bed represents the boundary between two large-scale sequences (one of Upper Tithonian–Upper Aptian stratigraphic range, and the other of Upper Albian–Upper Santonian age), and is therefore very important for the regional geological study of Istria and neighbouring areas (e.g. Ćićarija Mt., Island of Cres, etc.). The duration of the emersion phase was variable, from 11–19 MY, depending upon the palaeogeographic position of the different localities. During this period continental environments prevailed, although there are also relics of swamps with anoxic conditions. Sporadic aeolian import of volcaniclastic and siliciclastic material resulted in the formation of rather thick beds of clays and clayey marls which were subsequently altered by pedogenic processes during the long emersion phase.

Fig. 54. Lower Aptian oncoidal limestones in Kanfanar quarry.

Stop 3: *(Fantazija quarry)*

Berriasian cyclic alternation of macrocrystalline late-diagenetic and supratidal early-diagenetic dolomites in the old „Fantazija" quarry near Rovinj (western Istria)

Compiled and partly cited after*: Vlahović, I., Tišljar, J., Velić, I., Matičec, D., Skelton, P.W., Korbar, T. and Fuček, L.(2003): Main Events Recorded in the Sedimentary Succession of the Adriatic Carbonate Platform from the Oxfordian to the Upper Santonian in Istria (Croatia)*

The **Fantazija quarry**, protected as a natural geological monument, is situated approximately 2 km east of Rovinj. It was used for the trial exploitation of dolomites as architectural-building stone during the 1970's, but the material was too hard and fissured for regular use, and the quarry was soon abandoned. The local municipality, the Istrian County and the Ministry of Environmental Protection, are planning to arrange to use it for touristic purposes. The quarry is located within Berriasian dolomites (**Fig. 55**), which continuously overlie, either the more or less late-diagenetically dolomitised limestones of the Kirmenjak unit or a relatively thick succession of late-diagenetic dolomites (i.e. the completely dolomitised upper part of the Kirmenjak unit). The boundary between the Tithonian and Berriasian, i.e. between the Jurassic and Cretaceous, is located within the underlying late-diagenetic dolomites (see **Fig. 55**; it has been documented within incompletely dolomitised sequences). The thickness of the alternation of early-diagenetic and late-diagenetic *Fantazija dolomites* (**Fig. 55**; Velić & Tišljar, 1988) or the informal **Rovinj unit** (Vlahović, 1999) is variable, approximately 35 m on average. Due to the numerous well-preserved structural-textural characteristics in the early-diagenetic dolomites, the quarry was the object of several geological field trips (Tišljar et al., 1983, 1995, 2000).

In the Fantazija quarry, on smoothly cut walls, the rhythmic alternation of 0.4 to 1.2 m thick layers of dark grey macrocrystalline dolomites and 0.3 to 0.6 m thick beds of light grey supratidal early-diagenetic dolomites can be seen (Füchtbauer & Tišljar, 1975, Tišljar, 1976). Bedding planes between the two lithotypes are irregular and sharp, and the thicknesses of individual beds are usually variable.

This is a consequence of complex depositional processes:

(1) irregular early-diagenetic dolomitization of subtidal–intertidal sediments, as seen on the contacts of late-diagenetic dolomites and overlying early-diagenetic dolomite beds;

(2) irregular erosion of the surficial parts of deposits emerged into the supratidal zone, as visible on the upper bedding planes of light-coloured early-diagenetic dolomite beds;

(3) loading of rapidly lithified supratidal early-diagenetic dolomites into the underlying soft subtidal–intertidal sediments, as shown by numerous load casts, disintegration of light-coloured beds, and shrinkage cracks;

(4) irregular growth, shrinkage and convolution of laminated stromatolitic layers and laminae in the upper part of the light-coloured early-diagenetic dolomite beds, resulting in wavy laminae, tepee-structures and desiccation cracks;

(5) synsedimentary tectonic deformations: small-scale faults and probable seismites;
(6) some structures interpreted as dinoturbations.

While dark grey late-diagenetic dolomites are structure-less, light-coloured beds of early-diagenetic dolomites contain frequent structures, including fenestral fabric and stromatolite laminae, tepee-structures, load casts with disintegration of beds, desiccation and shrinkage cracks , supratidal breccia, tidal channels, eroded upper bedding surfaces, etc. Wavy laminations (**Fig. 55**) represent LLH stromatolites of a *Schizotrix* type. Desiccation cracks occur only within light grey early-diagenetic dolomite beds and on the upper bedding surfaces of some dark grey beds exposed in the upper intertidal zone. Small, mm-sized cracks within stromatolitic laminae are especially frequent. Larger, cm-sized desiccation cracks, filled with material from the overlying beds, are visible in places in both sections: in vertical sections they are "V"-shaped, while in horizontal section they are polygonal.

Deep shrinkage cracks occur only within the light-coloured early-diagenetic dolomites, and are filled with the material of the overlying dark beds, showing typical fillings . This is evidence that early-diagenetic dolomite beds were already relatively well lithified when cracks were formed, i.e. before deposition of the overlying fine-grained detritus in subtidal–intertidal environments, representing the next cycle. Additional evidence of early lithification is represented by the frequent disintegration of beds, brecciation and synsedimentary faulting of light-coloured beds, which is, in the underlying, soft beds manifested only by plastic deformation. All the aforementioned structures can be seen not only on the quarry walls, but also, and sometimes even better, on numerous blocks which are arranged around the quarry in their original orientation. These blocks represent 3D sections of one or several beds.

The composition and texture of light-coloured early-diagenetic dolomites and dark-coloured late-diagenetic dolomites are very different (**Fig. 55**). Dark grey beds have a homogeneous macrocrystalline mosaic dolomite sructure composed of hypidiotopic to xenotopic 0.1 to 0.4 mm long dolomite crystals, with frequent fine kerogen inclusions, generally zonally oriented within the dolomite crystals. Only rarely, in the wider vicinity of the quarry, especially in the lower and upper part of the dolomite succession, are incompletely dolomitized relics of subtidal–intertidal limestones (pelletal wackestone/packstones, grainstones and mudstones with stromatolitic laminae) found. This fact, in addition to the macrocrystalline structure and other sedimentological features, support the interpretation of dark grey dolomite beds as being the result of late-diagenetic dolomitisation of subtidal limestones (Füchtbauer & Tišljar, 1975).

Light-coloured dolomite beds (**Fig. 55**) are characterised by their variable composition and textures. Some beds or laminae are composed of cryptocrystalline dolomite (dolomicrites), weakly-sorted dolomite intraclasts and dolomite cements (dolointrasparite), dolomite peloids and pellets in dolomitic matrix or dolomite cement (dolopelmicrites and dolopelsparites). Some beds represent dolomite fenestral LLH stromatolites, usually in the upper parts of light-coloured beds. Fenestral fabric is common, usually laminoid, rarely irregular (**Fig. 55**), always filled with transparent dolomite cement, and in places with internal sediment – vadose crystal silt with geopetal characteristics. Intraclasts, pellets and peloids were transported by high tides and storms from subtidal areas to intertidal and supratidal zones. Larger intraclasts, especially those composed of supratidal breccia, were formed by the disintegration and reworking of early-lithified upper parts of emerged sediments. Dolomite crystals composing pellets, intraclasts, peloids, dolomicritic laminae and cryptalgal laminae are generally smaller than 10 µm, while dolomite crystals in intergranular pores range in size from 10–30 µm.

Fig. 55. Berriasian early- and late-diagenetic dolomites in Fantazija quarry.

Stop 4 *(Cape Zlatni Rt, S of Rovinj)*

Hiatus between the uppermost Oxfordian or basal Kimmeridgian and the Upper Tithonian deposits

Compiled and partly cited after*: Vlahović, I., Tišljar, J., Velić, I., Matičec, D., Skelton, P.W., Korbar, T. and Fuček, L. (2003): Main Events Recorded in the Sedimentary Succession of the Adriatic Carbonate Platform from the Oxfordian to the Upper Santonian in Istria (Croatia)*

Stop 4 (**Fig. 56**) comprise the final part of the 1st large-scale sequence (Bathonian–Oxfordian/lowermost Kimmeridgian) and the beginning of the second large-scale sequence (Upper Tithonian–Lower/Upper Aptian) of Istrian deposits.

The large-scale Bathonian–Oxfordian sequence, (approximately 200 m thick) is characterised by coarsening- and shallowing-upward trends and terminated by the Kimmeridgian–Early Tithonian emersion with bauxite deposits. This large-scale sequence is divided into four informal lithostratigraphic units (Velić & Tišljar, 1988):

Unit 1 – **"Monsena micrites"** composed of mudstones and wackestones deposited during the Bathonian, Callovian and Early Oxfordian in lagoonal and subtidal environments;

Unit 2 – **"Lim pelletal limestones"** i.e. well-bedded (0.3–0.8 m), fine grained, "soft", porous pelletal packstones/wackestones of uniform structure, packing and appearance. They were deposited during the Oxfordian in low-energy subtidal environments (near fair-weather wave base) which pass laterally into Unit 3. The thickness of this unit (35–50 m) depends on the relationship and frequency of the appearance of Unit 3 – **"Muča ooid-bioclastic limestones"***,* as these units alternate both vertically and laterally.

Unit 3 – **"Muča ooid-bioclastic limestones"** in fact positioned within Unit 2 – "Lim pelletal limestones" as a lateral facies equivalent, in the form of relatively long lenses, some tens of metres thick. In zones of lateral transition one facies wedges out, interfingering with the other, giving an impression of a vertical sequence of lentoid strata. At the Muča peninsula (northern part of Rovinj) in a typical locality, the thickness of this unit is 47 m.

Unit 4 – The **"Rovinj/Vrsar breccia and bauxites"** includes limestone breccia and bauxite. Breccia occurs in a continuous belt regularly overlying the **Lim units** or **Muča units**, and underlying the next Upper Jurassic unit – ***"the Kirmenjak stylolitised micrites"*** as the first unit of the 2nd large-scale sequence Upper Tithonian–Lower/Upper Aptian. Breccias were formed as a result of a sea-level fall and emersion, and bauxite deposits formed during the emersion phase from the (Late Oxfordian?) earliest Kimmeridgian to the beginning of the Late Tithonian (Velić & Tišljar, 1988).

At the coast and in the neighbouring quarry in the area of the **Zlatni Rt ("Golden Cape")** forest park S of Rovinj (**Fig. 56**), we will see one type of contact between two large-scale sequences, characterized by smaller emersions in the underlying deposits. The first large-scale sequence of Istrian deposits is represented by a 9 m thick succession of ooid–

bioclastic deposits. This would correspond to the c member of the informal Muča unit, consisting of an ooid grainstone matrix with variable amounts of large (2–55 mm) coated bioclasts of Cladocoropsis, other stromatoporoid hydrozoans, corals, pachyodont bivalves, and tests of benthic foraminifera deposited by tidal currents and waves, before their final deposition as a carbonate sand tidal-bar (Tišljar & Velić, 1987), in some places characterised by cross-bedding. 30–50 cm thick beds of peloid and skeletal wackestone (representing a member of the informal **Muča unit**) are less frequent.

The boundary between the large-scale sequences is, at this locality, characterized by an irregular surface and up to 50 cm thick bed of black-pebble breccia with clayey matrix. These deposits represent the beginning of the oscillatory transgression over the emerged relief, i.e. the beginning of deposition of the informal Kirmenjak unit. This unit is named after the small village in central Istria where the main quarries of this type of stone are located. *The Kirmenjak stone* has been a famous architectural-building stone for centuries (even from the Roman times), and was especially important during the construction of Venice, Ravenna and Loret, when many buildings and palaces were built from this material (known as ***„Pietra d'Istria"*** or **"*Istrian Stone*"**).

In the ancient quarry on the **Zlatni Rt cape** (**Fig. 56**), an approximately 35 m thick sequence of the **Kirmenjak unit** crops out, characterized by typical shallowing-upward cycles, and its upper part is late-diagenetically dolomitized, which is also characteristic of this unit. The **Kirmenjak unit** represents the first part of the second transgressive–regressive large-scale sequence of Jurassic–Cretaceous shallow-water carbonates of Western Istria. Generally, it is composed of different shallowing-upward cycles consisting of three members (Tišljar et al., 1995):

(1) a thin, laterally variable bed of black-pebble breccia with carbonate, clayey or marly matrix. This member was formed by the redeposition of material originating from marsh deposits enriched in organic matter, which was eroded and transported during a relative sea-level rise.
(2) a thick (100 to 200 cm) stylolitised mudstone with rare bioclasts of *Clypeina jurassica* FAVRE, *Salpingoporella annulata* CAROZZI and *Campbelliella striata* (CAROZZI). In some cycles its upper part is characterised by vertical bioturbation, fenestral fabric, desiccation cracks and erosion surfaces. This member was deposited in a low-energy subtidal environment.
(3) the upper part of cycles are characterised by variation in thickness, lithology and structural fabric. They are predominantly represented by vadose fabrics, intraclasts with pisoid coatings, and in places by thinner or thicker stromatolites. The upper bedding surfaces are sharp, irregular with desiccation cracks and/or erosion features. This member was formed in an intertidal and/or vadose zone.

Fig. 56. Zlatni Rt cape (**S of Rovinj**), with 1st large-scale sequence (Bathonian–Oxfordian/lowermost Kimmeridgian) and the beginning of the second large-scale sequence (Upper Tithonian–Lower/Upper Aptian) of Istrian deposits.

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